

FILE

U

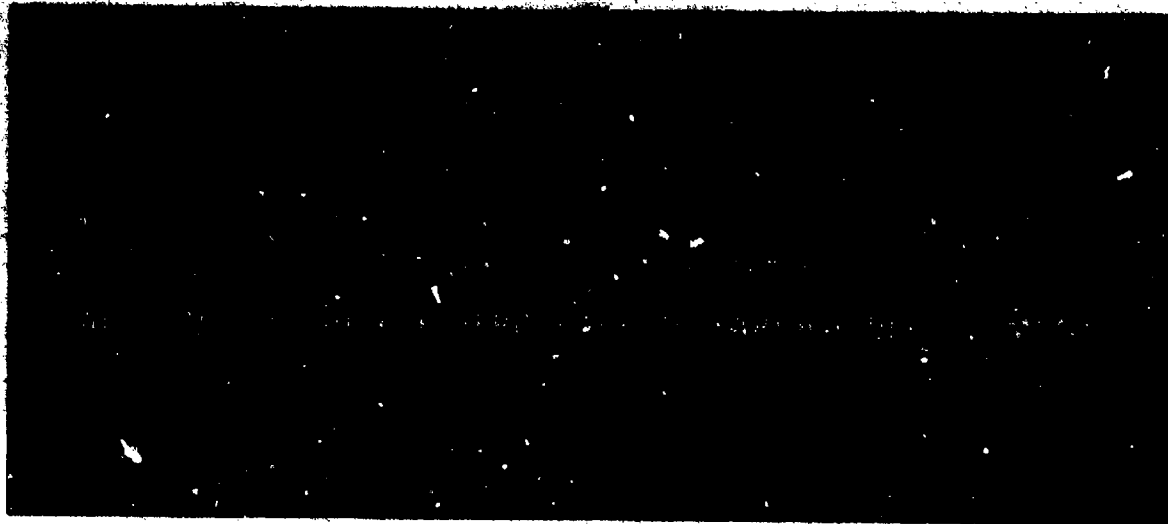
AGARD-AG-160-VOL.B

AG 160 VOL. 13

PRACTICAL ASPECTS OF INSTRUMENTATION SYSTEM INSTALLATION

AGARD-AG-160-VOL.B

AD A107355



AGARDograph No. 160

**AGARD Flight Test Instrumentation Series
Volume 13**

on

**Practical Aspects of
Instrumentation System Installation**

by

R. W. Borek

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

DTIC
ELECTE
NOV 16 1981



DISTRIBUTION AND AVAILABILITY

FORM 10-22-50-1

11 10 087

(14)
AGARD-AG-160-VOL-13
Volume 13

NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

DTIC
ELECTE
NOV 16 1981
H

AGARDograph No. 160 Vol. 13

PRACTICAL ASPECTS OF INSTRUMENTATION SYSTEM INSTALLATION.

by
R.W. Borek

AGARD Flight Test Instrumentation Series

Volume 13.

Practical Aspects of Instrumentation
System Installation

of the

AGARD FLIGHT TEST INSTRUMENTATION SERIES

Edited by

10
11
Robert W. Borek

A. Pool and K.C. Sanderson

11 Sep 81

12 1991

DISTRIBUTION STATEMENT A

Approved for public release.
Distribution Unlimited

This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD

400043

LB

THE MISSION OF AGARD

The mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

- Exchanging of scientific and technical information;
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

The content of this publication has been reproduced
directly from material supplied by AGARD or the authors

Published September 1981

Copyright © AGARD 1981
All Rights Reserved

ISBN 92-835-1399-1



*Printed by Technical Editing and Reproduction Ltd
Harford House, 7-9 Charlotte St, London, W1P 1HD*

PREFACE

Soon after its founding in 1952, the Advisory Group for Aerospace Research and Development recognized the need for a comprehensive publication on flight test techniques and the associated instrumentation. Under the direction of the AGARD Flight Test Panel (now the Flight Mechanics Panel), a Flight Test Manual was published in the years 1954 to 1956. The Manual was divided into four volumes: I. Performance, II. Stability and Control, III. Instrumentation Catalog, and IV. Instrumentation Systems.

Since then flight test instrumentation has developed rapidly in a broad field of sophisticated techniques. In view of this development the Flight Test Instrumentation Group of the Flight Mechanics Panel was asked in 1968 to update Volumes III and IV of the Flight Test Manual. Upon the advice of the Group, the Panel decided that Volume III would not be continued and that Volume IV would be replaced by a series of separately published monographs on selected subjects of flight test instrumentation: The AGARD Flight Test Instrumentation Series. The first volume of the Series gives a general introduction to the basic principles of flight test instrumentation engineering and is composed from contributions by several specialized authors. Each of the other volumes provides a more detailed treatise by a specialist on a selected instrumentation subject. Mr W.D.Mace and Mr A.Pool were willing to accept the responsibility of editing the Series, and Prof.D.Bosman assisted them in editing the introductory volume. In 1975 Mr K.C.Sanderson succeeded Mr Mace as an editor. AGARD was fortunate in finding competent editors and authors willing to contribute their knowledge and to spend considerable time in the preparation of this Series.

It is hoped that this Series will satisfy the existing need for specialized documentation in the field of flight test instrumentation and as such may promote a better understanding between the flight test engineer and the instrumentation and data processing specialists. Such understanding is essential for the efficient design and execution of flight test programs.

The efforts of the Flight Test Instrumentation Group members (J.Moreau CEV/FR, H.Bothe DFVLR/GE, J.T.M. van Doorn and A.Pool NLR/NE, E.J.Norris A&AEE/UK, K.C.Sanderson NASA/US) and the assistance of the Flight Mechanics Panel in the preparation of this Series are greatly appreciated.

F.N.STOLIKER
Member, Flight Mechanics Panel
Chairman, Flight Test
Instrumentation Group

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	

SUMMARY

Following the selection of the instrumentation system, a suitable installation must be developed. Factors that influence this development are the subject of this volume.

The material is presented in a progressive manner starting with a review of the mission profile requirements. Included are such factors as environment, reliability and maintainability, and system safety.

The assessment of the mission profile is followed by an overview of electrical and mechanical installation factors. The material presented is primarily directed at shock/vibration isolation systems and standardization of the electrical wiring installation, two factors often overlooked by instrumentation engineers.

A discussion of installation hardware reviews the performance capabilities of wiring, connectors, fuses and circuit breakers, and so forth. Information is provided to guide proper selections.

The discussion of the installation is primarily concerned with the electrical wire routing, shield terminations and grounding. Also included are some examples of installation mistakes that could affect system accuracy.

The remaining two sections discuss system verification procedures and special considerations such as sneak circuits, pyrotechnics, aircraft antenna patterns, and lightning strikes.

TABLE OF CONTENTS

SUMMARY	Page
	iv
SYMBOLS AND ABBREVIATIONS	ix
1.0 GENERAL	1
2.0 CONCEPTUAL DEVELOPMENT OF AN INSTRUMENTATION SYSTEM INSTALLATION	2
2.1 Environmental Criteria	2
2.1.1 General Applications	2
2.1.2 Specific Applications	2
2.1.3 State-of-the-Art Exceptions	2
2.2 Determination of Environmental Requirements	3
2.2.1 Assess Mission Profile	3
2.2.2 Establish the Environmental Conditions	3
2.2.3 Determine Standards and Specifications	4
2.2.4 Document the Results	4
2.3 Environmental Factors	4
2.3.1 Temperature	5
2.3.2 Pressure	8
2.3.3 Shock, Vibration and Related Sources of Stress	8
2.3.4 Moisture	10
2.3.5 Electromagnetic Interference (EMI)	10
2.4 Reliability	12
2.4.1 The Early Failure	12
2.4.2 The Wearing Out of Parts	12
2.4.3 The Chance Failure	12
2.4.4 Failure Occurrence	12
2.4.5 Reliability Design Practices	12
2.4.6 Stresses	13
2.4.7 Anomalies	13
2.5 Maintainability	13
2.5.1 Accessibility	13
2.5.2 Cable Routing	14
2.5.3 Minimize Maintenance Errors	14
2.5.4 Temperature Considerations	14
2.6 Safety Requirements	15
2.6.1 Environmental Considerations	15
2.6.2 Termination Arrangement	16
2.6.3 Protective Devices	16
2.6.4 Material Selection	17
2.6.5 Fire, Toxic Fumes, and Operation in Hazardous Atmosphere	17
2.6.6 Personnel and Equipment - Safety Relationships	18
3.0 SYSTEM INSTALLATION DESIGN MANAGEMENT	20
3.1 Interrelation of Systems	20
3.1.1 Mechanical Interface	20
3.1.2 Electrical Interface	20
3.1.3 Electronic Interface	20
3.1.4 Integrated Design	20
3.2 Design Management	20
3.2.1 Available Installation Space	21
3.2.2 Weight Control	21
3.3 Instrumentation Installation Diagrams	21
3.3.1 The Block Diagram	21
3.3.2 Connection Diagrams	24
3.3.3 The Schematic Diagram	25
3.3.4 Instrumentation System Wiring Diagrams	26

	Page
3.4 Instrumentation Subsystem Compatibility	30
3.4.1 Interference Coupling at Low Frequencies	30
3.4.2 Interference Coupling at High Frequencies	35
3.4.3 General Grounding Considerations	35
3.4.4 Data Signal Grounds (Low Level)	37
3.4.5 Reducing Conductive EMI	40
3.4.6 Bonding	41
3.4.7 Conduit Grounds	41
3.4.8 The Bond Strap	41
3.5 Protective Isolation Systems	43
3.5.1 Shock and Vibration Damping	43
3.5.2 Isolators	44
3.5.3 Stabilizers	47
4.0 SELECTION OF INSTALLATION HARDWARE	48
4.1 Connector Selection Considerations	48
4.1.1 Conflicting Military Specifications and Vendor Catalogs	48
4.1.2 Connector Environmental Considerations	50
4.1.3 Selection of Connectors	52
4.1.4 Procurement Considerations	57
4.1.5 Connector Selection Checklist	57
4.2 Selection of a Forced-Air Convection Cooling System	58
4.2.1 Factors That Influence the Choice of Blower Application	58
4.2.2 Example - Determination of a Finned Heat Sink and Selection of a Blower (Fan)	58
4.3 Selection of Mechanical Isolators	63
4.3.1 Underneath Mounting Systems	64
4.3.2 Center-of-Gravity Mounting Systems	65
4.3.3 Double Side Mounting Systems	65
4.3.4 Over-and-Under Mounting Systems	65
4.3.5 Inclined Isolator Mounting System	65
4.4 Selection of Displays and Controls for Crew Area	66
4.4.1 Displays	66
4.4.2 Controls	67
4.5 Selecting Fuses and Circuit Breakers	68
4.5.1 Fuses	69
4.5.2 Circuit Breakers	73
4.5.3 Limiters	76
4.5.4 Fuse/Limiter Comparison	78
4.5.5 Reliability After Inspection	78
4.6 The Selection of Wires and Cables	78
4.6.1 Wire Gages	78
4.6.2 Circular Mills (CM)	80
4.6.3 The AN Wire Gage Size	80
4.6.4 Wire Construction	80
4.6.5 Wire Gage Selection	90
4.6.6 Example - Selection of a Wire Conductor and Its Insulation Material	96
4.6.7 Selection of Flat Cables	98
4.7 Selection of Modular Terminal Junctions	104
4.7.1 Electrical Considerations	105
4.7.2 Mechanical Considerations	105
4.7.3 Environmental Considerations	107
5.0 INSTALLATION OF THE INSTRUMENTATION SYSTEM	109
5.1 Wiring Harness Routing and Installation	109
5.1.1 Harness Protection	109
5.1.2 Harness Routing	110
5.1.3 Support Clamping	111
5.1.4 Cable Shield Terminations	112
5.1.5 Connector Mating	117
5.1.6 Connector Inspection	119
5.1.7 Connector Protection	120

5.2	Determination of Wire Bundle Size	Page 120
5.3	Equipment Location	121
5.4	Installation Procedures that Minimize EMI	123
5.4.1	Wire Classification and Harnessing	123
5.4.2	Separation Design Limits	125
5.4.3	Separation Compromises	125
5.4.4	Special Wiring	126
5.4.5	Ground Wires	126
5.4.6	Ground Studs	126
5.4.7	Engineering Control	127
5.4.8	Miscellaneous EMI De-Coupling Methods	128
5.5	EMI Control During Installation and Maintenance of Crew Area Switches and Displays	129
5.5.1	Design Guidelines	130
5.5.2	Special Installation Requirements	130
5.5.3	Typical EMI Installation Problems and Solutions	131
5.6	Transducer Installation Considerations	132
5.6.1	Microphone Installation	132
5.6.2	Pressure Tubing Contaminants	132
5.6.3	Nose Boom Transducers	133
5.6.4	Strain Gages	133
6.0	INSTRUMENTATION SYSTEM VERIFICATION AND DOCUMENTATION	135
6.1	System Verification and Calibration Procedures	135
6.2	Instrumentation System Calibration	135
6.3	Review Boards	136
6.3.1	Design Engineering Review (DER)	136
6.3.2	Operational Readiness Review (ORR)	136
6.3.3	Board Functions	137
6.3.4	Responsibilities and Procedures	137
6.3.5	Operational Readiness Review Checklist	138
6.4	Record Keeping and Documentation	139
6.4.1	Wire Lists	139
6.4.2	Connector Lists	140
6.4.3	Other Examples of Record Keeping	141
6.4.4	The Parameter Line-Up Sheet	142
7.0	SPECIAL CONSIDERATIONS	145
7.1	Sneak Analysis	145
7.1.1	Sneak Circuit Analysis	145
7.1.2	Types of Sneak Conditions	145
7.1.3	Instrumentation Systems and Sneak Analysis	146
7.1.4	Examples of Sneak Analysis Reports	147
7.2	Pyrotechnic Devices	153
7.2.1	Pyrotechnic Terminology	154
7.2.2	General Description of Initiators	154
7.2.3	Connectors and Wiring	157
7.2.4	Power Sources	158
7.2.5	System Design Philosophy	158
7.2.6	Pyrotechnic System Checkout	158
7.2.7	Static Charges and Unexpected Firings	158
7.2.8	Disposal and Inerting	160
7.2.9	Pyrotechnic Operations - Safety Checklist	160
7.2.10	Circuit Design Considerations	162
7.2.11	Documentation	163
7.3	Aircraft Antenna Patterns	163
7.3.1	The Coordinate System	164
7.3.2	Explanation of Antenna Patterns	165
7.3.3	Pattern Correlation	168
7.3.4	Quantitative Use of Pattern Data	170
7.3.5	Reciprocity of Radiation Patterns	173

										Page
7.4	Lightning and Static Electricity	.	.	.	.	.	.	.	.	173
7.4.1	Lightning	.	.	.	.	.	.	.	.	173
7.4.2	Precipitation Static	.	.	.	.	.	.	.	.	177
8.0	REFERENCES	.	.	.	.	.	.	.	.	181

SYMBOLS AND ABBREVIATIONS

A	area
A_1, A_2	load determination dimensions
A_I	current amplifier
A_V	voltage amplifier
ADF	Automatic Direction Finder
AN	Aircraft Number (wire gage)
AWG	American Wire Gage
a	wire diameter
ac	alternating current
alt	altitude
B_1, B_2	load determination dimensions
b	basic ratio
C_1, C_2	distributed capacitance relative to distances r_1 and r_2
C_a, C_b	stray capacitance to ground
C_c	coupling capacitance
C_k	coefficient of kinetic friction
C_s	coefficient of static friction
CG	center of gravity
CM	circular mils
CW	continuous wave
D	wire bundle diameter
D	diameter of one strand of a wire
DDC	Defense Department Contract
d	diameter of a wire
dc	direct current
E	field intensity
E	emissivity
E	induced voltage, volts
E_{cm}	common-mode voltage
E_{nm}	normal mode voltage
E_o	interference voltage
E_s	signal voltage
E_x	interference voltage coupled to adjacent wire
E_x	plus excitation voltage
$-E_x$	negative excitation voltage
EED	electroexplosive device
EMI	Electromagnetic Interference
EMF	electromotive force

F_c	the force pressing the friction surfaces together
F_s	force required to overcome static friction
FCC	flat conductor cable
FFC	flat flexible cable
f	frequency
G	antenna gain
GS	Glide Slope
HF	High Frequency
h	heat transfer coefficient
I	current, amperes
I_{cm}	common-mode current
I_k	force required to move an object with uniform velocity against friction
I_s	signal current
I_x	induced current causing a noise voltage at R_1
K	coupling efficiency
L	length
LF	low frequency
LOC	localizer
l	twisted wire pair length
MF	Medium Frequency
\dot{m}	air mass flow rate
NOM	nominal
n	Wire-pair twists per meter
OAS	over all shield
P	power density
P_t	power transmitted
Q	heat dissipated
R	distance
R_1, R_2	signal source resistance to amplifier input terminal
R_3, R_4	leakage resistance to system ground through amplifier input terminal
R_o	resistance of a conductor at temperature, t_o
R_t	thermal resistance
R_t	total circuit resistance
R_t	resistance of a conductor at temperature, t
R_x	total resistive impedance
RF	radio frequency
RNDU	remote multiplexer digitizer unit
RWC	round wire cable

r_{ms}	root mean square
r_1	loop spacing
r_2	loop spacing
+SIG	plus signal voltage
-SIG	negative signal voltage
SL	sea level
t_1	equipment (heat sink) temperature, °C
t_2	air temperature, °C
UHF	ultra high frequency
V	signal level at receiver input
\dot{V}	volumetric flow rate
V_s	signal voltage
VHF	very high frequency
VOR	VHF omni range
W	width specified by the customer
W	weight of equipment with connectors and cables
W_r	power delivered to load by receiving antenna
W_t	transmitted power
$Z_1, Z_2,$ Z_3, Z_4	load impedances
Z_b	impedance of C_b
Z_c	impedance of C_c
Z_x	impedance
α	temperature coefficient of resistivity
λ	wavelength
θ	pitch plane, spherical coordinate system
μ	permeability
ρ	air density
ρ_a	air density at altitude
ρ_{SL}	air density at sea level
σ	Stefan-Boltzman constant
ϕ	yaw plane, spherical coordinate system

PRACTICAL ASPECTS OF INSTRUMENTATION

SYSTEM INSTALLATION

Robert W. Borek
Flight Mission Operations
NASA Dryden Flight Research Center
Post Office Box 273
Edwards, California 93523
USA

1.0 GENERAL

This volume has been written to preserve experience, share the practical lessons learned and present information that can be useful in the installation of aircraft instrumentation systems.

In order to limit the subject material, certain baseline conditions have been assumed concerning the data acquisition system.

1. The program objectives have been established.
2. The instrumentation system has been selected, bench tested and proven.
3. The transducers for the parameters to be measured have been selected, tested and proven.

The practical aspects of instrumentation installation includes a tremendous amount of subject material. Accordingly, a treatise discussing the available material will probably never be complete. The real value then in an effort such as this is to discuss those areas of instrumentation installation that are oftentimes subjects of concern. This information should be particularly valuable to the novice instrumentation engineer who lacks adequate resources to guide his installation.

The suggestions and guidelines contained within this volume may be somewhat subjective. Terminology is a good example of an area where a difference of opinion may exist. One example is the use of the word hardware. For editorial purposes the accepted use of the word was modified in order to place a broad amount of material in one section (Section 4.0).

There are no two engineers who are alike, either by educational background, professional responsibilities or both. As a result parts of the material in this volume may be inappropriate for some and deficient for others. There are some flight test agencies that assign several engineers to one aircraft and conversely, other agencies that assign several aircraft to one engineer. In the former case, the engineer may be limited to responsibilities that involve only the basic data acquisition system. Regarding the latter case, which is most likely more common, to assure a quality installation the engineer must be concerned with not only the basic data acquisition system, but all other electrical/electronic phenomena not assigned to someone else. For example, such phenomena as lightning and precipitation static, electromagnetic interference, and onboard telemetry antennas are often subjects that require the instrumentation engineer's attention. (Throughout this volume the terms "engineer" and "instrumentation engineer" will be used interchangeably).

Practical experience has shown that if problems exist in any of the above named areas it is usually the instrumentation engineer that gets involved. For this reason Section 7.0, Special Considerations, was included in this volume to provide information in these areas. For example, discussions of lightning strikes and antenna pattern correlation are not readily found in off-the-shelf texts.

The second problem mentioned above was the inability to separate and completely discuss certain subjects. Shielding is such a subject. Shielding is multi-faceted and deserves separate attention when discussing transducer installation, pyrotechnics and lightning strikes. For example, shielding techniques used for protecting aircraft wiring from lightning strikes are different from the techniques used for basic aircraft wiring, yet both requirements must be accommodated simultaneously. Therefore, discussions of shielding techniques are presented in the appropriate sections and referenced from other sections where appropriate.

One final comment is necessary. This volume was not written with the intention of being a design handbook. The guidelines presented are in most cases given as suggestions. This was done for two reasons. First, each instrumentation system is unique and what works well for one installation may not work equally well for another. Second, the manner in which the material is presented is only meant to call attention to potential problem areas and not to provide a universal solution. In short, the instrumentation engineer must carefully think through his own problems using the material in this volume as a guideline whenever applicable.

2.0 CONCEPTUAL DEVELOPMENT OF AN INSTRUMENTATION SYSTEM INSTALLATION

Environment, probably more than any other factor, influences the installation design of systems and subsystems in and on an aircraft. Thinking in terms of an instrumentation subsystem, aircraft environment is quite often the primary reason for its installation. During the installation design phase, it simplifies the environmental analysis to separate environments into two broad categories: natural and induced. Environments are generally thought of individually. Separating them into two broad categories will assist in isolating specific design problems. Natural environment consists of the various physical day-to-day phenomena that are routinely encountered. However, in addition to these natural environments, aircraft are also subjected to induced environments brought about strictly by the operation of the aircraft and its subsystems. Typical examples are elevated internal and external aircraft temperatures due to high Mach numbers, shock and vibration, and electromagnetic interference due to conductive coupling.

A well-designed, well-engineered, thoroughly tested, and properly maintained instrumentation system should not fail in operation. Experience has shown that the occurrence of failures cannot be completely eliminated. In specifying reliability requirements, the cost of assembling an instrumentation system is weighed against the cost and effects of in-service failures. This is an important point because with a given reliability designed and built into a system, the average rate of failures is also built into the system. Reliability and maintainability are characteristics that can be both created and destroyed. Their creation is a result of careful planning, designing, testing and ultimately using a product or system according to a set of specified procedures. Their destruction results from lack of awareness of the procedures used during the assembly of the product or installation of the system/subsystem. Ref. (B1)

The identification and integration of system safety requirements are vital parts of an effective instrumentation installation in that these requirements serve as the interface between a safe installation design and its safe operation and maintenance. Safety requirements are quite often factored into equipment and hardware procurement and installation guidelines. Typical examples are equipment environmental requirements and unit weight and size.

2.1 Environmental Criteria

An engineer must have firm environmental limits from which to work if he is to design or develop an instrumentation system installation in a practical manner. He must know exactly the environments to which each part of the system is to be exposed so that the completed installation will operate satisfactorily. Special environmental requirements are often derived from the performance characteristics of the aircraft.

2.1.1 General Applications

An environmental analysis for a general application usually is not as definitive as that for a specific application, but it should include more environments because of its broader scope. Therefore, mission profiles of various types of aircraft must be carefully analyzed to determine environmental requirements.

2.1.2 Specific Applications

The environmental requirements for a specific aircraft installation will result in a detailed approach since more information is available to aid in defining the requirements. For this reason, an environmental analysis for a hypothetical installation is usually performed. The analysis must include the flight vehicle and its subsystems, equipments and compartments. Wherever the instrumentation is to be installed, it should be designed to function properly even under conditions which may only occur rarely.

2.1.3 State-of-the-Art Exceptions

In specific cases involving unique aircraft, it may be found that the state-of-the-art may not allow an installation to be operational over the entire range of its environment. Under these circumstances there is a tendency to favor the environmental extremes, e.g. high temperature. This could create a problem if the vehicle's mission requires low temperature operations. For example, a high performance aircraft with high temperature aerodynamic heating conditions based in the Arctic may experience failures in components or hardware due to their inadequate low temperature characteristics. Where there is doubt concerning the significance of any environmental value, an operational analysis should be performed to determine the validity of the value. In the above example of high temperatures due to aerodynamic heating, the vehicle skin temperature may be 300° C (572° F), but because of airframe insulation the temperature internal to the instrumentation component may be less than half of that value. An analysis may also show that the high temperature values represent brief or infrequent transient values and the duration of low temperature conditions might be lengthy. Thus, from a practical viewpoint the low temperature requirements are more important.

2.2 Determination of Environmental Requirements

As pointed out earlier, the instrumentation engineer must have environmental limits to work with. The procurement and installation of instrumentation equipment and hardware depend on knowing these limits. In circumstances where environmental information is not known or at best minimal, the following suggestions may be helpful.

- a. Obtain as much data as possible relevant to the mission profiles.
- b. Establish the environmental conditions.
- c. Determine environmental standards or specifications.
- d. Document the results.

2.2.1 Assess Mission Profile

The mission profile is one of the most important factors to be considered when making a determination of environmental requirements. The altitudes at which the vehicle is to be tested, the speeds at which it will travel, and the type of flight test conditions are of prime concern. For example, smooth or turbulent air, for which data is to be obtained will provide the instrumentation engineer with a set of guidelines within which the system must satisfactorily operate.

Alternate mission profiles should also be part of the basic plan. On occasion the unexpected happens, and a well planned instrumentation system will take full advantage of its designed capabilities should the true environment not fall within the environmental design requirements.

Each phase of the aircraft's mission profile must be carefully reviewed to determine the extent of induced environments. Profiles for ground operations and storage should also be included. Oftentimes protective covers must be made to protect instrumentation sensors.

2.2.2 Establish the Environmental Conditions

Review the aircraft mission profile and performance to establish the environmental conditions to be encountered during flight testing such as altitude, temperature ranges, turbulence, vibration, and internal temperatures. It is important to review both the exterior as well as the interior environments of the aircraft. These determinations should be reviewed for each location where instrumentation is to be installed. Ref. (1)

2.2.2.1 Natural Environments

Conventional aircraft depend upon aerodynamic forces for their operation; as a result their entire mission is confined to the earth's atmosphere. Accordingly, they may be subjected to any combination of the natural environments. The probability of encountering any particular type of natural environment depends to a great extent upon where the aircraft is operating. For example, flight test conditions in the desert regions are far different from flight test conditions in tropical areas.

2.2.2.2 Induced Environments

The type and severity of induced environments encountered by conventional aircraft depend primarily on the type of aircraft and its performance requirements. For example, when operating from an aircraft carrier greater accelerations may be experienced during takeoff and landing than during conventional operations.

The types and combinations of induced environments are highly variable. For example, aerodynamic heating and boundary turbulence are only a concern under certain conditions of flight, and if these conditions are being investigated, then the instrumentation installation must not only acquire the desired data, but operationally survive as well. In fact, it is these induced environmental conditions that present one of the greatest challenges to the instrumentation engineer. It is his responsibility to use established environmental criteria and then design an installation that will be safe, reliable and effective. Ref. (2)

2.2.2.3 Unique Environmental Conditions

In some instances particularly those caused by induced environments, the standard environmental criteria will not be very helpful. This is particularly true for environmental limitations relevant to the interiors of compartments. In such cases tests may be made by instrumenting a mockup under simulated conditions. Or, if the locations do not present an extreme environment they can be instrumented in the aircraft and evaluated during flight test.

2.2.2.4 Combined Environments

It is interesting to note that most of the environmental test specifications presently available are based on single environments. Very little data exists on effects of the various combinations of environments that may be encountered in actual flight testing. In use, a system will never encounter any single environment by itself. Even though combinations of environments are encountered, the extremes usually occur singly, and it is these extremes that are the most important. Do not overlook the possibility that the extreme of one environment may intensify the effects of the other. Combinations of natural and induced environments always exist together.

2.2.3 Determine Standards and Specifications

A few of the more important specifications and standards that provide environmental design information for aircraft are listed in Table 2.2-1. The standards and specifications in this table have been grouped according to their application. Although the titles explain their contents, two in particular warrant brief discussion.

2.2.3.1 MIL-STD-210

One of the more important standards is MIL-STD-210. This standard is an outgrowth of equipment failures experienced during World War II. The standard establishes uniform climatic design criteria for air, land and Arctic use. The information provided represents conditions of natural environment, not induced environment. Although this specification (and the others also), relate only to military equipment and hardware it goes without saying that an instrumentation installation must survive in the same environment as the system or subsystem it is monitoring. Ref. (3).

2.2.3.2 MIL-W-5088

The MIL-W-5088 specification was initially published in March 1951, superseding the AN-W-14a specification dated May 1945. Then, as now, the specifications covered the selection and installation of wiring and wiring devices used in aerospace vehicles. The initial intent was to establish design criteria for wiring an aerospace vehicle; not as a guide for subsequent instrumentation installations. Fortunately, however, over the thirty years since its inception sufficient supporting data has been added to this Mil Specification to provide guidance useful for instrumentation installations. Ref. (4). (See Section 4.6.5)

2.2.4 Document the Results

The accumulated environmental data must be compiled and documented in report form or at least in such a manner so that it is available for others to use. The written results should be clear, concise and complete. Further, the sources, methods and techniques used to determine the environmental data should be included. If mockups or simulations are used to assist in determining environmental data values, then these procedures and results should also be included in the final document.

2.3 Environmental Factors

The most practical method available for designing an environmentally qualified instrumentation installation is to use available hardware and equipment developed to meet the specified environmental requirements. Experience has shown, however, that this method is not always possible. As a result various types of environmental control must be used to accommodate environmentally limited hardware

Table 2.2-1 Specification and Standards - Listing Some of the Environmental Requirements for Aerospace Vehicles

IDENTIFICATION	TITLE
FLIGHT VEHICLES	
MIL-I-5289	Instrumentation Installation for Climatic Test of Aircraft, General Specification for
AIRBORNE EQUIPMENT	
MIL-E-8189	Electronic Equipment, Missiles, Booster and Allied Vehicles, General Specifications for
MIL-E-5400	Electronic Equipment, Airborne General Specifications for
MIL-E-6051	Electromagnetic Compatibility Requirements, Systems
MIL-STD-461	Electromagnetic Interference Characteristics Requirements for Equipment
MIL-W-5088	Wiring, Aerospace Vehicle
ENVIRONMENTAL FACTORS	
MIL-STD-210	Climatic Extremes for Military Equipment
AEROSPACE GROUND EQUIPMENT	
MIL-E-4158	Electronic Equipment Ground; General Requirements for
MIL-S-008512	Support Equipment, Aeronautical Special, General Specifications for the Design of
MIL-T-21200	Test Equipment, for Use with Electronic and Fire Control Systems, General Specification
MATERIALS	
MIL-P-9024	Packaging, Materials Handling and Transportability, System and System Segments, General Specification for

and equipment. Environmental control generally requires consideration of temperature, pressure, corrosion, shock and vibration, and EMI shielding. Refs. (5, 6).

2.3.1 Temperature

One factor that must be taken into consideration in all combinations since it is present in all environments is temperature. This must be distinguished from heat. Heat is a form of energy, while temperature is a factor affecting the availability of energy. In a quiescent state an instrumentation system is influenced by the temperature resulting from heat generated by solar radiation and by ambient air temperatures. System operation adds additional heat sources that contribute to surface and compartment temperatures. At supersonic speeds, aerodynamic heating becomes the predominant factor, followed by electronic and propulsion equipment heating, and then by solar radiation.

2.3.1.1 Heat-Producing Sources

Aircraft surface and compartment temperatures result from one or more of the four major heat sources: ambient air temperature, solar radiation, aerodynamic heating and heat producing equipment.

- a. Ambient air temperature - On the ground, ambient air temperature is influenced by geographical location, season, prevailing winds, atmospheric conditions and the nature of the earth's surface.
- b. Solar radiation - Direct absorption of solar energy can increase aircraft surface and compartment temperatures to well above the ambient air temperatures. Solar radiation is of particular importance to aircraft parked in the open. Depending upon the parking surface and the reflectivity of the aircraft surface, varied amounts of direct and reflected radiation is absorbed. If the flight vehicle's thermal capacity and heat transfer capabilities are high, the absorbed heat will be stored in the material or distributed around the aircraft surface with moderate temperature changes. If the thermal capacity is small, temperature will rise more rapidly.
- c. Aerodynamic heating - This is the heat produced by the compression and friction of air sliding over the surfaces of the aircraft. This heating is proportional to the square of the Mach number. However, for Mach 1 and below the temperature rise can usually be ignored. The relationship of stagnation temperature and Mach number is shown in Figure 2.3-1. It should be observed that high temperatures become a factor at speeds exceeding Mach 2. Ref. (B2).
- d. Heat producing equipment - At speeds of Mach 1 and below the principal source of flight vehicle heat is the equipment within the flight vehicle itself: electronic equipment, electrical rotating equipment, electrical power systems, and mission related systems. Although the heat produced by any item of equipment could be critical, the major internal heat sources are generally the electrical and electronic systems. The trend toward miniaturization has only compounded the problem. Smaller electrical units have made space for additional equipment. The result has been a requirement for more electrical power and increased heating. In turn, the additional units increase compartment temperatures and often create "hot spots" that are difficult to design around. Heating is also a critical factor in the compartments surrounding the aircraft engines and APU's. Although thermal insulation is used, sufficient heat is still transferred to these areas to severely restrict their use for many instrumentation system components.

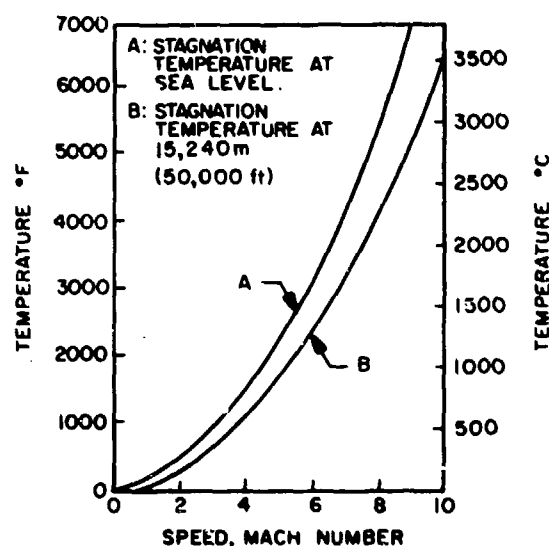


Figure 2.3-1 Temperature vs. Mach Number

2.3.1.2 Temperature Control Methods

The primary objective of employing temperature control is to prevent excessive temperature rise on and within the flight vehicle. Excessive heat buildup can be prevented or removed by using either a passive or active heat removal system. Passive systems use insulation and heat sinks, whereas active systems use a combination of passive plus cooling air (forced convection or blowers) to minimize the temperature buildup.

2.3.1.2.1 Compartments

If the interior of the flight vehicle is one large open space, the heat from the hot equipments will flow toward and heat the cooler equipment. By dividing the interior of the vehicle into compartments and properly locating the heat-generating equipment and those equipments that need heating it is possible to neutralize the negative effects of both types of equipments. If this approach is not possible, then the heat-generating equipments should be located near the aircraft structure so that the structure may act as a heat sink, assuming, of course, that the aircraft skin will not be at a higher temperature than the equipment. Dividing the interior of the vehicle into compartments does not guarantee that the heat problem will be solved. The temperatures in the cooler compartments may still rise due to conduction through the walls. The conduction problem may be minimized, however, by insulating the walls to reduce conduction and/or by the use of inter-compartment or inner wall air flow.

2.3.1.2.2 Compartment Wall Insulation

Effective reduction of heat transfer to a compartment depends on the amount and type of insulation used and its placement. An inner wall airspace has good insulating qualities, but the use of insulating material results in improved qualities. The trade-off is in the insulation type, thickness and weight.

The emissivity of the insulating material should also be considered since radiation can contribute a considerable portion of the thermal load to a compartment. The use of aluminum foil-backed insulation will substantially reduce the interchange of radiant energy.

In practice, the effectiveness of the insulation is reduced by insulation compacting and moisture absorption. Thus the effective thickness of the insulation is less than the actual thickness. The effects of insulation on the total thermal load of a compartment is shown in Table 2.3-1. Ref. (B2).

The data shown in this table indicates that the total heat transfer is reduced by more than 40% by completely insulating each compartment wall with 1.3 centimeters (0.5 inch) of Fiberglas. The total heat flow is reduced an additional 23% by doubling the thickness of insulation. Again, each wall must be completely insulated.

Table 2.3-1. Example of Heat Transfer, Insulated Compartment Walls.

AMOUNT OF INSULATION	HEAT FLOW,	
	JOULES/MIN x 10	(BTU/MIN)
Standard insulation - 1.27 cm (0.5 inch) of Fiberglas over 25% of compartment area.	620	(587)
1.27 cm (0.5 inch) of Fiberglas overall.	354	(335)
2.54 cm (1.0 inch) of Fiberglas overall.	214	(203)

2.3.1.2.3 Intercompartment and Inner Wall Air Flow

The use of intercompartment and inner wall airflow is a very effective method for removal of excessive heat build-up. The intercompartment heat removal is done by discharging cooling air into the heated compartment, thus reducing the heat transfer through common walls. Table 2.3-2 shows the effectiveness of inter-compartment air flow.

Table 2.3-2 Example of the Effects of Intercompartment Airflow.

CONDITION	HEAT FLOW,	
	JOULES/MIN $\times 10^3$	(BTU/MIN)
No intercompartment air flow; belly skin and floor uninsulated.	204	(193)
No intercompartment air flow; belly skin insulated only.	96	(91)
Intercompartment air flow; belly skin and floor uninsulated.	160	(169)
Intercompartment air flow; belly skin insulated only.	32	(30)

The heat-flow between compartments can be reduced further by discharging the cooling air through the inner wall. This procedure is considered practical only for small compartments in high-speed vehicles because of the difficulty in equalizing the air flow rates (see Section 2.3.2.1).

2.3.1.2.4 Choice and Location of Heat Sources

The amount of heat generated by equipment can be noticeably influenced by the choice of available designs, while location within a compartment can determine the problems that will result from generated heat. Each item of equipment should be reviewed and selected as based on the following guidelines:

- Does the equipment selected generate minimum heat? For example, solid-state units usually generate less heat than their conventional equivalents. It should be noted, however, that replacing one item of equipment with another requires reviewing the substitute's environmental capabilities. It is possible that the substitute item may not perform satisfactorily within the environmental ranges required.
- Can the item be located so that the heat from it will not be directed to other items within the compartment? To prevent inter-compartment "hot spots," equipments with a high heat output should be well separated from each other, and if possible, away from units that must remain cool. In most cases these two suggestions are mutually exclusive. The priority is to disperse the hotter items in order to prevent "hot spots." Then, if necessary, use heat shields between hot and cooler equipments. The heat shields should be attached to heat sinks so that a conduction path for the heat transfer is present. If these procedures are not sufficient then consider the addition of a forced convection heat-removal system, in which case grouping the high heat generators together may be desirable.

2.3.1.2.5 Heat Removal Methods

Regardless of the passive temperature protection methods used, the complexity of today's aircraft creates heat build-up in available compartment space that often makes the installation of flight test instrumentation very complex. Very often available areas within the aircraft cannot be used until provisions are made for removal of heat generated by the aircraft systems and by the instrumentation system.

Heat removal is the process of conducting heat from a heat source to a heat sink.

- Conductive Heat Transfer.** Heat is transferred by conduction from one object to another only when they are in direct physical contact.
- Convective Heat Transfer.** The process of heat transfer from the surface of a solid to a moving mass of fluid, either gaseous or liquid, is called convection.
- Radiant Heat Transfer.** Objects emit radiation ranging in wave length from the far infra-red to the ultra-violet. The radiation from an object can travel through a vacuum or through gases with very little absorption. The radiation upon being intercepted by another object will be partly reflected and partly reradiated. Heat transfer by radiation does not require physical contact.

2.3.1.2.6 Cooling by Conduction

Effective conductive cooling requires materials that are thermally highly conductive. The thermal conductivity of metals is generally directly proportional to their electrical conductivity. Accordingly, conduction cooling requires good metal-to-metal contacts. Quite often the thermal contact resistance is minimized by high temperature soldering, brazing, or welding. For removable items of equipment when conductive cooling heat sinks are used, the metal-to-metal bond is enhanced by using silicone grease. Installation methods are presented in Section 4.2.1.2.

2.3.2 Pressure

Based on the assumption that both the instrumentation system and its transducers have been selected and environmentally proven, the effects of pressure on the overall installation will be divided into two categories based on pressure altitude: Environmental cooling variations and electrical arc-over and corona.

2.3.2.1 Environmental Cooling

Since the density of air decreases with an increase of altitude, the heat absorbing capacity of air decreases accordingly. Table 2.3-3 presents the heat-absorbing capacity of a given volume of air at various altitudes as a percentage of its heat absorbing capacity at sea level.

Convection is a common method often used for the removal of heat from equipment and since the air is less able to absorb and remove heat at higher altitudes, the temperature of heat producing components may rise above safe operating levels.

At a pressure altitude of approximately 13,700 meters (45,000 feet), air should no longer be considered as a heat conductor. Under these circumstances, equipment that needs cooling should be mounted in an environmentally controlled area (see Section 4.2) and/or mounted to a cooled conductive surface.

Table 2.3-3. Reduction of Heat Absorbing Capacity of Air With Altitude.

ALTITUDE METERS (FEET)	HEAT ABSORBING CAPACITY OF GIVEN VOLUME OF AIR AS PERCENTAGE OF THAT AT SEA LEVEL
0	100
6,096 (20,000)	50
12,192 (40,000)	25
18,288 (60,000)	10
24,384 (80,000)	3
30,480 (100,000)	1

2.3.2.2 Electrical Arc-Over and Corona

The insulating effect of air between high-voltage electrodes or other high-tension points decreases with decreasing pressure. At high altitudes, unpressurized high voltage equipment may have a voltage arc-over between the high-tension points. At a pressure altitude of 12,200 meters (40,000 feet) the voltage breakdown potential is about 25% of the sea level threshold. At 18,300 meters (60,000 feet) the voltage breakdown potential is 12.5% of the sea level threshold. Connectors, terminal strips, and relay contacts are subject to arc-over problems. If voltages are not high enough or the air pressure is not quite low enough to support arc-over, minute arcs may take place in the area of the high-voltage points. This is known as corona and can damage components and material as well as causing considerable RF interference. Corona initiation potentials are known to be greatly reduced by the presence of dust, oil, component material corrosion, and chemical reaction from previous corona occurrences. Connectors and terminations exposed to extreme altitude environments should be inspected and thoroughly cleaned, if necessary, prior to re-exposure.

2.3.3 Shock, Vibration and Related Sources of Stress

In general, shock and vibration are treated as separate and distinct phenomena. Yet the distinction between the two is often difficult to determine. For example, the difference between transient shock motion and periodic vibration is clear, but the differences between shock and random vibration, which is not periodic, is not obvious. For purposes of this discussion, shock will be considered as intermittent excitation and vibration as sustained excitation.

2.3.3.1 Shock

Shock implies an impact, a collision, or a blow usually caused by physical contact. It represents a rapid change of loading or a rapid change of acceleration, with a resultant change of load. A shock motion can be defined by describing the history of an associated parameter such as acceleration, velocity,

or displacement. Acceleration is the time rate of change of velocity. Acceleration is used in defining shock; the implication of a relatively sudden change in acceleration is always present. Acceleration by itself does not constitute shock. For example, an aircraft subjected to steady-state acceleration is not undergoing shock.

Shock occurs when a structure is subjected to a suddenly applied force, resulting in transient vibration of that structure at its natural frequencies. The magnitude of the vibration may be great enough to cause fracturing of brittle material or yielding of ductile material. A secondary effect of shock is that large accelerations, characteristic of the abrupt changes associated with shock, may be transmitted to equipment and components supported within a structure. This secondary effect should be of major concern to the instrumentation engineer designing an instrumentation system installation.

2.3.3.2 Vibration

Vibration can be described as the variation, with time, of the magnitude of a quantity to a specified reference, when the magnitude is alternately greater or smaller than the reference. Vibration is in essence periodic, but this periodic nature may be disguised if several unrelated frequencies occur simultaneously. Purely "white" vibration (in which all frequencies and amplitudes have equal probability) seldom occurs. Usually even in seemingly random vibrations two or more frequencies will predominate.

2.3.3.3 Acoustic Vibration

Intense acoustic pressure loads are generated by the noise from turbo-jets, ramjets, rocket engines, and aerodynamic boundary layers. The high levels of sound impinge on the aircraft skin and are converted to mechanical energy that can reach instrumentation sensors, as well as supportive electronics, in the form of vibration.

2.3.3.4 Shock and Vibration Protection

There are two broad methods of protecting an instrumentation installation against the effects of shock and vibration: (1) select components and design techniques that can withstand the shock and vibration environments; (2) where the environments are too severe, it will be necessary to carefully locate and orient components and equipment and most likely use isolation protection devices.

2.3.3.5 Sources of Shock, Vibration, and Acceleration

A quick review of the aircraft mission profile will usually identify most of the sources of shock, vibration, and acceleration. A few are listed below:

- a. Flying through turbulent air.
- b. Maneuvers resulting in severe load factors.
- c. Imbalance in reciprocating power plants.
- d. High speed induced aircraft flutter.
- e. Hard landings such as aircraft carrier requirements.
- f. Firing of weapons.

All of the above sources can be considered as being external to the aircraft. The list does not include internal effects from rotating or moving equipment such as pumps, compressors, or actuators that generate vibrations of multiple frequencies and amplitudes. Further, component failures should not always be considered a result of the aircraft mission profile, even if all the evidence indicates it. Consider the following example:

The problem involved the failure of a miniature relay and its glass seal. The bottom view of the relay and a cross section of one of its pin contacts is shown in Figure 2.3-2.

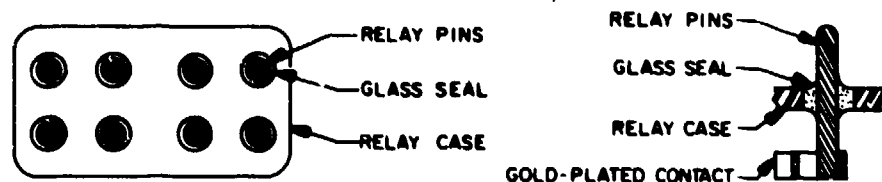


Figure 2.3-2 Bottom View of Relay and Cross Section of One of Its Pin Contacts

The printed circuit mounting specification required that all component leads that mount on printed circuit boards should not protrude through the board more than 0.76 millimeter (0.030 inch). The excess lead lengths were routinely clipped off. The relay failure consisted of cracked glass seals surrounding the pin contact. The cause of the failure was determined to be a result of the shock occurring during the process of clipping off the excess length of the relay pin contact. At the instant of final metal separation, during clipping, rather severe forces (or shock waves) were transferred to the pin contact. Future problems were averted by not clipping these pin contacts.

2.3.4 Moisture

Moisture is a term often used to mean humidity as well as various forms of condensation and precipitation. Specifically, moisture is a liquid and is usually water that is diffused or condensed in relatively small quantities. Water in the form of vapor is always present in varying amounts in the atmosphere. This vapor content in the atmosphere is referred to as humidity. When the temperature of the air is reduced below the dew point, condensation occurs. In general, dew formation takes place when a given surface is above 0° C (32° F). If the temperature is below 0° C (32° F), the condensation will form frost. In some cases, supercooled droplets will form which later freeze to form ice. Heat loss from radiation may cause sufficient cooling for the formation of dew.

Condensation can frequently be induced in an aircraft by changes in altitude. The colder upper altitudes lower the air temperature within the aircraft, and if the air is relatively moist, it can be sufficiently cooled to condense moisture upon the equipment and hardware within compartments.

2.3.4.1 Accelerated Corrosion

Moisture combined with dust and pollutant gases may result in an alkaline, acid, or saline solution capable of causing accelerated corrosion. The pollutant gases may originate independently of the aircraft environment or they may be a direct result of the aircraft itself. Typical aircraft sources are fuel vapors, fuel exhaust vapor, and gases due to weapon firings.

In tropical areas the combination of dust and moisture may nourish microbiological growth which produces further deterioration such as accelerated corrosion or fungi.

2.3.4.2 Fungi

Most fungi have an optimum temperature range of 15° C to 35° C (59° F to 95° F), although there are forms that will grow at lower and higher temperature extremes. The average optimum temperature for fungi growth is 30° C (85° F), with relative humidity at 95 to 100 percent. Below 70 percent relative humidity there is little opportunity for fungi growth. Other than high relative humidity and a suitable temperature, the only additional requirement for fungi to thrive is abundant food. This is supplied in large amounts by a great variety of organic materials produced by vegetation. Cordage, paints, adhesives, plastics, resins, rubber are mostly made of organic materials and thus are susceptible to fungi. Furthermore, fungi do not attack organic materials alone, but some forms will attack metals, glass, and clay products.

2.3.4.3 Moisture and Fungus Protection

In general there are three methods of protecting against the effects of moisture and fungi. The most direct method is to carefully select fungus and corrosion-resistant materials. The second method is to apply a protective coating on the item of hardware to be used, or on the completed assembly. This method is not to be relied upon unless the entire assembly can be fully immersed in the coating agent. A third method is to hermetically seal the equipment or item of hardware. This method is effective but limited, since not all items of hardware can be sealed in this manner. The best method is to use combinations of all three methods.

2.3.5 Electromagnetic Interference (EMI)

When electronic systems are connected together, problems can arise in the form of EMI. EMI is interference which is created by the coupling of noise from one subsystem to another by means of conductive paths or by radiation. The term most often used to categorize the entire area of the EMI problem is "EMI Environment." Accordingly, EMI is introduced into this discussion as a part of the total aircraft environment. Since most instrumentation installations are primarily concerned with conductive paths rather than radiation, the discussion will focus its attention to that area. Ref. (7, 8)(B3).

2.3.5.1 Responsibility for EMI Solutions

One of the least defined portions of the EMI problem is that of responsibility. The overall responsibility for the control of EMI should rest within a central authority within the prime organization. However, it is usually the instrumentation system that is affected by EMI and as a result it is the instrumen-

tation engineer who must solve his own problems. To solve these problems a procedure must be established to gather meaningful data.

The EMI data to be gathered that are relevant to the EMI environment are of two types. The first type lists the values of susceptibility for each of the various subsystems as referenced to an established noise level. The second type lists the individual contributions made by each subsystem to the overall system noise level. The susceptibility data should define the noise levels that adversely affect each subsystem. The noise output data should define the individual values of noise level and their location on each of the wires that are part of the subsystem so that conducted noise levels can be traced. Both EMI data listings should use units of voltage and current rather than decibels. The frequency spectrum of each level noted should also be identified.

2.3.5.2 EMI Data Gathering

The possibility of an EMI problem can be estimated prior to the installation from derived block diagrams that represent the instrumentation installation and include the following information:

- a. Location of the subsystem within the aircraft.
- b. Electrical wiring data. (Available from the manufacturer)
 - (1) Capacitance/per unit of length.
 - (2) Inductance/per unit of length.
 - (3) Resistance/per unit of length.
- c. Power and signal levels.
 - (1) Frequency components.
 - (2) Current and voltage levels.
 - (3) Source impedances.
 - (4) Load impedances.

It should be pointed out that the above information should be based on worst case conditions.

The first step then, from "a" above is to locate the subsystems within the aircraft. This is done by using the mechanical installation drawings and positioning the subsystems by using the following criteria:

1. Subsystem (or transducer) requirements. A subsystem may need a particular position in the aircraft due to the type of measurement it must make (for example, center-of-gravity or boundary-layer measurements).
2. Subsystem function. Subsystems may need to be located with respect to the function that they perform. For example, a data acquisition subsystem that is used to monitor data from only one part of the aircraft should be located close to that area to reduce transducer wire lead lengths.
3. Power and weight. Subsystems which require high currents should be located as close to their power source as possible in order to reduce the effects of cabling impedances. (Weight is also important to the static and dynamic balance of the aircraft and must be considered when locating the subsystem.)

Once the location of the subsystem has been decided, an estimate can be made of the routing of the cables. This will provide the basis for the information needed in step b.

From the cable routing information, the length of each cable can be estimated. Then from the manufacturer's wiring data, the per-unit-length of capacitance, inductance, and resistance can be determined. These unit-values multiplied by the total cable length will provide the values to be used in any computations required for installation analysis. For example, these values can be used to calculate the reactance values of a transducer circuit wiring.

The power and signal levels, step c, for each of the wires within the various cables are then obtained for each subsystem. These levels of current and voltage along with their frequency components can be used in conjunction with values of source and load impedances and cable data to compute the values of conducted EMI.

If calculations are necessary, the results can be used to establish limits that define the immunity that each subsystem must achieve.

2.4 Reliability

The reliability of a product (or system) is generally defined as the probability that the product will give satisfactory performance for a specified period of time when used under specified conditions. Whenever the definition is applied to a particular system it is always necessary to relate probability to a precise definition of satisfactory performance.

Instrumentation systems are often one-of-a-kind, and system reliability is at best difficult to determine. However, the determination of component reliability is much easier, since many of the individual components are repeatedly used in a wide variety of instrumentation systems. Over a period of years the instrumentation engineer should develop a listing of trouble-free components and hardware based upon past experience. The phrase "trouble-free" is used because the average instrumentation engineer does not usually think in terms of statistical reliability. Reliability statistically identifies three types of failure characteristics.

1. The early failure.
2. The wearing out of parts.
3. The chance failure.

2.4.1 The Early Failure

The early failure usually results from poor quality components (or hardware) or deficient design techniques. These failures are usually corrected by using standard "trouble-shooting" techniques. These failures may be observed during initial system operation or during the first flight mission. The early failure can be minimized by using thoroughly tested and proven components, hardware, and approved design installation procedures.

2.4.2 The Wearing Out of Parts

This type of failure is indicative of little or no system maintenance. These types of failures can usually be minimized by properly scheduled maintenance and by upgrading the replacement parts.

2.4.3 The Chance Failure

These types of failures occur unexpectedly and at irregular intervals. The occurrence of chance failures cannot be predicted, and it is not normally easy to eliminate their occurrence.

2.4.4 Failure Occurrence

The three types of failures outlined above are each distinct and separate for two reasons. First, each type follows a specific statistical dimension, and second, different methods must be used for their elimination.

Unfortunately, early failures and wear out failures occur more often than they should. Early failures are often injected into an instrumentation system every time it is repaired or modified, either by an improper selection of replacement components for those that have failed or by some faulty routing of wiring or electrical connection. In a similar way wear out failures can make an inherently reliable system very unreliable. In general, however, such wear out failure occurs as an unexpected fault induced by poor maintenance. (Ref B1.) The important point here is that the equipment or component is not at fault.

The so-called "chance" failure cannot be eliminated by good maintenance practices or by any debugging or trouble shooting technique. Although not predictable the chance failure does follow certain rules of behavior such that the frequency of their occurrence over a long period of time is approximately constant.

2.4.5 Reliability Design Practices

Further discussion of the three types of failures must lead into the mathematics of reliability. Fortunately, the instrumentation engineer has two design techniques that can usually offset lengthy calculations. The first of these tools is equipment or component derating; the second tool, redundancy, is used for instances when even derating may not help.

2.4.5.1 Equipment or Component Derating

Components are designed to withstand certain operational stresses, that is they are rated for a definite operating voltage, current, vibration, temperature, etc. It can be assumed that when these rated limits are exceeded, the failure rate will rapidly increase. On the other hand, the failure rate decreases when the operational stresses are less than the rated value. For example, if a component is to operate at its rated stress, a reduction of its environmental stresses

will reduce the component's failure rate. For circumstances where reducing these environmental stresses adds too much system weight, costs too much or are not practical, then an alternate solution is to use a component of double rating and operate it at one half its rated stress value. In most cases, this may be less costly. An ideal situation exists when the environmental stress is reduced and the component is derated.

2.4.5.2 Redundancy

Redundancy is an effective but very expensive method of attaining a desired level of reliability. The use of redundancy is not a solution to all reliability problems, nor is it a substitute for good design. Its very nature implies increased weight, complexity, space and power; not to mention a usually more complicated system checkout. The sum total of all this is added cost in one form or another. However, redundancy may be the only solution to some of the problems that confront the instrumentation engineer.

2.4.6 Stresses

The stresses that influence components can generally be grouped into two categories: environmental and operational.

Environmental stresses are present whether a component in a system is actively operating or in a quiescent state. Typical natural environmental conditions such as temperature, pressure, humidity, and solar radiation may cause a deterioration of component strength which may affect its useful life. In addition to the natural environment, if induced environments such as vibration and shock occur, then these combined stresses can cause a chance failure.

Operating stresses appear only when the component is in active operation. These stresses normally lead to chance failures, but at the same time they also contribute significantly to component deterioration resulting in wearout.

2.4.7 Anomalies

Anomalies can be resolved in three ways. First, the anomaly can be proved to be caused by a procedural error that can be demonstrated and repeated. Second, the anomaly can be explained by specific hardware failure. Replacement and proper validated operation indicates a proper solution to the anomaly. The third type of anomaly is the worst case condition: The anomaly cannot be explained or repeated. The lack of a definite explanation makes it impossible to "fix" the fault. Therefore, the action is to analyze the fault and perhaps apply proper redundancy to achieve the intended operation.

2.5 Maintainability

Inherent maintainability must be established as part of the installation during the design phase. The design goal is to produce a system installation for which maintenance can be performed safely, quickly, easily, accurately and economically. Ref. (9, 10).

2.5.1 Accessibility

Accessibility implies that a component or assembly can be approached with relative ease for purposes of installation, removal or maintenance. A lack of adequate access will often result in ineffective maintenance because personnel may omit or delay maintenance of equipment or hardware that cannot easily be seen or reached.

2.5.1.1 Access Location Determinations

The type, size, shape and location of access to an aircraft instrumentation installation is generally determined by the following:

- a. Operational location and environmental capabilities of the equipment to be installed.
- b. Frequency of required accessibility.
- c. The type of maintenance to be performed through the access.
- d. The type of test, equipment, calibrations and time necessary to perform the required operation on the equipment.
- e. The amount of space required to perform work on the installation.
- f. Visual requirements.
- g. Physical size of equipment behind the access.
- h. Hazards inherent to the access itself, such as location near moving parts, hot exhausts, high voltages or toxic fumes.

2.5.1.2 Access Design Considerations

Access includes entrance doors, inspection plates, and servicing points. If possible, design the access cover plates large enough and in the proper shape to allow hardware and equipment installation, servicing, and removals. Whenever possible use hinged or captive covers. If this is not possible, then use a minimum number of screws when designing the access plate. Shape code the access plate if it must be installed in a certain way. Captive, quick-opening fasteners that do not require special tools for opening or closing are preferred. Depending on the size of the aircraft and the program requirements the following suggestions may also be helpful:

- a. Label each access area with its purpose. Clearly identify it with a unique number or letter code.
- b. If at all possible, provide visual access in areas where there is danger from nearby electrical circuits when maintenance of these circuits is required.
- c. Make battery accesses large enough to permit safe handling, test, maintenance or replacement.
- d. Consider human factors when designing accesses. This type of effort will assure optimum accessibility for all items requiring maintenance, inspection or removal.

2.5.2 Cable Routing

Wiring is probably the most difficult type of electrical installation to remove and replace and is almost impossible to reroute once it has been installed. Further, regardless of how durable it may appear to be it is vulnerable to damage by handling during installation and maintenance. And finally wiring is often in the way when associated electrical equipment needs attention. However, many of the problems encountered relating to wiring and cable installations can be minimized if careful planning is made a part of the installation design phase.

Whenever possible, individual wires and cables should be assembled into harnesses that are held together by clamps and ties. If an advantage in routing can be identified early in the installation design it can minimize less desirable routings as the design develops. Routings should be selected which do not obstruct access to ports, ducts, disconnects, terminals or equipment that may require removal or adjustments. Avoid routing wire in cramped areas which will prevent the inevitable growth of the wire bundle. Also consider the mechanical operation of equipment or systems in the areas chosen for routing the wiring. Wiring and harnesses must not interfere with aircraft operations.

Wiring should be routed so as to avoid damage from fluids or vapors. If this is not possible, then provisions must be made to protect the wiring. Remain clear of fluid lines since future failures of these lines may require maintenance. In all cases, remain clear of lines carrying flammable fluids.

Wiring is often routed near access doors. If routed near the bottom of an access door, the wiring is subject to abrasive contact damage by the installation and removal of equipment or by the entry and departing of operating personnel. If the wiring is routed near the top or sides of the door, they may provide inviting hand holds for personnel entering and leaving the vehicle. The alternatives are obvious: route the wiring away from the access doors in such a manner as to prevent their abuse. If this is not possible, then provide for protection of the wiring.

2.5.3 Minimize Maintenance Errors

Design subsystem interfaces such that equipment cannot physically be installed improperly. Use proper connector keying, coded shapes, asymmetrical mounts and other means to prevent inadvertent maintenance errors. (See Section 5.1.5 for methods of connector keying.) Design for rapid positive identification of each item of equipment. In-house designed and built equipment should have an identification tag affixed to it listing name of equipment, serial number and drawing number as a minimum. Ref. (11).

Minimize the complexity of maintenance by using a simple design which includes interchangeability and standardized components. Reduce excessive maintenance time by using latches instead of screws. The use of latches facilitates rapid access to the equipment as well as eliminating loose or lost hardware, such as screws that may cause electrical or mechanical failures.

2.5.4 Temperature Considerations

Excessive temperatures due to current flow, e.g., those that exceed the wiring specifications, can cause a failure in two ways:

- a. A breakdown of the insulation occurs.

b. Altered conductivity characteristics of the conductor.

The effects of insulation breakdown at high temperatures is well known. It usually melts and/or sublimates exposing the bare conductor. The altering of the conductor characteristics is not so well known. Briefly, as the temperature increases, the resistance of the conductor increases. The higher resistance in turn will cause the temperature of the conductor and its insulation to rise further. This effect if it continues will damage the connector contacts and will result in complete failure at the point when the conductor melts, breaking continuity and/or the insulation fails, causing an electrical short.

High ambient temperatures can also cause problems. For example, consider a sealed compartment of an aircraft sitting on the flight line under hot tropical conditions. In flight, this compartment is cooled and is maintained at reasonable operating conditions of low temperature and low humidity. Sitting on the flight line, however, the compartment is closed and the air conditioning turned off. The direct sunlight shining on the vehicle can raise the internal temperature to very high levels. If the compartment temperature is rapidly lowered in preparation for operation, as it might be during taxi, moisture may condense within the compartment. This moisture may well cause problems related to the connector electrical contacts unless adequate precautions have been taken. At the same time the thermal shock caused by the cooling effect can also cause interfacing of unlike materials to distort. Seals may open and insulation may crack or rupture.

This type of environment can cause the corrosion of connector contacts and connector shells. The extent of damage will depend on the chemical characteristics of the metals used. Typical metals that are used for shell construction to prevent this corrosion are anodized aluminum, stainless steel or non-metals. Contact materials are discussed in Section 4.1.3.2.

Temperatures below the specified wiring characteristics do not usually cause conductivity troubles in a wiring system. In fact, the lower the temperature, the more current a given conductor can carry. However, low temperatures can cause wiring insulation to become brittle with subsequent failure during vibration.

2.6 Safety Requirements

The installation design of an instrumentation subsystem in an aerospace vehicle requires careful consideration since it interfaces with nearly all other subsystems. Considering this complex interrelation, it is reasonable to assume that a failure in one subsystem may affect one or more of the others unless the installation design approach minimizes this possibility. Inherent safety in electrical/electronic systems must begin in the early stages of design. Appropriate review of safety requirements and objectives are important steps toward a proper installation. Ref. (B4).

2.6.1 Environmental Considerations

The components of the instrumentation system undergo a number of environmental extremes which must be considered before its performance can be predicted. The failure of a component because of unanticipated and severe service conditions can present a serious safety problem. The environment and its severity must therefore be an uppermost consideration.

2.6.1.1 Temperature

The engineer must verify that the system design is unaffected by temperature extremes, or that it is compensated so that temperature changes do not affect the system function. Provide for equipment cooling by selecting the most efficient heat-dissipating components, and by locating equipment out of areas of high environmental temperatures. Whenever possible, provide augmented cooling by using forced air in cases where normal heat dissipation is inadequate. Circulate the air within the equipment to achieve maximum heat-transfer from the major heat-generating parts, with the lower heat generators closest to the incoming air. Minimize leakage of cooling air to reduce the volume of cooling air required.

2.6.1.2 Pressure

It must be determined that the equipment is not degraded in operation because of the effects of altitude and sudden altitude changes. Employ hermetic sealing and pressurization to preclude corona, electrical arcing between components, or damage to pressure sensitive components which will be operated in low ambient pressure or which are affected by a rapid change of pressure, i.e. poorly vented instruments.

2.6.1.3 Vibration and Shock

The effect of aircraft vibration requires careful consideration. The design must incorporate only equipment or components qualified to meet anticipated vibration levels in all axes. In addition, specify fastening methods which prevent components from loosening and damaging adjacent equipment.

2.6.1.4 Humidity and Fungus

Select hardware that is capable of withstanding humidity up to 100% whether directly ambient or indirectly by condensation, in and on the equipment. Include in this consideration the exposure to salt-sea atmosphere and ensure that electrical termination points (connectors, terminals, splices, etc.) are given protection to eliminate their susceptibility to the hazards of this environment. Moisture collection at electrical terminal points cannot be tolerated. Select hardware which will not be degraded physically or functionally by exposure to fungus growth found in tropical climates; otherwise, provide exposed surfaces with protective coatings.

2.6.1.5 Hazardous Fluids

Combustible vapor is likely to be present in many areas of the aircraft. Use only those components or equipments which are incapable of causing ignition in an explosive atmosphere.

2.6.2 Termination Arrangement

Avoid the termination of power and signal leads on adjacent pins of a connector where possible. Isolate the wiring of critical circuits so that a single short circuit occurring in a connector cannot affect other components. Use separate connectors if practicable. Always consider the possibility of an inadvertent pin-to-pin short circuit within the connector. Arrange terminations to minimize this potential short-circuit hazard. Do not terminate the elements of a redundant circuit in a single connector where the loss of such a connector will negate the redundant feature.

Use terminal junction blocks only for wires and cables requiring infrequent disconnection. Provide for adequate spacing between junctions to prevent leakage currents between circuits under extremes of environment. Physically isolate circuits which are degraded by proximity to other circuits. (See Section 4.7)

Workmanship is the key to connector and junction block dependability and system safety. Therefore, the design cannot be considered complete until the special techniques, tools, materials, and processes involved in production are clearly specified.

2.6.3 Protective Devices

Provide protective devices for primary circuits and other such circuits as required for protection from damage as a result of overloads or extreme service conditions. Protect circuits, equipment, or parts which may be overloaded because of malfunction, improper adjustment, component casualty, or other degrading effects by employing isolation techniques in the circuit design. In addition, ensure that the design incorporates protective safety features for personnel during the installation, operation, maintenance, and repair of a complete equipment assembly or its component parts.

2.6.3.1 Location

Locate fuses or breakers where they can be seen and replaced or reset without removing other components. If possible, group the location in a central, easily accessible area, and provide for spare fuses to be located near the fuse holder. Identify each fuse for its proper value. Fuse caps of a quick-disconnect type are preferred over the screw-type; ensure that they are knurled and easily removable by hand.

2.6.3.2 Detection

Provide a means such as telltale lights or other sensory aids which will promote the rapid detection of a blown fuse or breaker by the crew member concerned.

2.6.3.3 Temperature Effects

Consider the operating temperatures in the area where the protective fuse or breaker is to be used. The fuse rating must be adjusted up or down (uprating or derating) to allow for the added or subtracted heat provided by the operating environment. This design consideration is necessary to ensure that the device has a dynamic factor of safety under expected service conditions. The specific electrical overload protection varies greatly according to the intended use.

2.6.3.4 Multiple Circuit Protection

Do not allow several critical electrical components to be protected by a single circuit breaker or fuse. An electrical short in a single component can cause the circuit breaker (or fuse) to shut off power to the other components. Provide multiple circuit protection where necessary.

2.6.4 Material Selection

The selection guidelines for suitable standard parts and materials used in the design and fabrication of the aircraft instrumentation system have been carefully documented. However, various safety requirements may demand the selection of materials which are not covered by these specifications. In determining the suitability of parts and materials, give consideration to the following:

- a. The space and weight limitations placed on the total installation.
- b. The interchangeability of the parts with those in the drawings.
- c. The parts and materials must be qualified to meet the performance and environmental requirements imposed by the aircraft.

When possible, incorporate in the installation those items having both the broadest characteristics and the greatest allowable electrical tolerances that will fulfill the performance requirement of the system.

2.6.4.1 Stability

Several factors should be considered before selecting materials for a specific function. The materials should be consistent and uniform with regard to their chemical properties. Ensure that they are compatible with their operating environment and are resistant to corrosion, fungi, moisture, temperature extremes, sunlight, ozone, dust, and other service conditions. They must not be capable of supporting combustion.

Anticipate unusual service conditions and select only the best possible materials to meet the requirements. Specify metallic parts which are corrosion resistant or provide for the use of a protective coating. Avoid the use of coatings or finishes which may degrade the material properties, or are subject to chipping, cracking, or scaling. Similarly, suitably protect nonmetallic parts against deterioration as a result of contamination by oil, grease, or environmental elements.

2.6.4.2 Toxic Materials

Avoid the selection of materials that will liberate toxic gases or liquids under adverse operating conditions. Select materials that are easily fabricated and repaired with a minimum of time or of special equipment. Ensure that assembly and maintenance is consistent with average human effort, ability, and attitude. The use of standardized materials, types, sizes, etc., is an aid in expediting field maintenance.

2.6.4.3 Dissimilar Metals

Avoid the use of dissimilar metals that easily corrode. In the presence of an electrolyte, such as moisture, electrolytic corrosion ensues. Corrosion, aside from physical degradation, destroys the operational and safety objectives of electrical bonding. The adverse effect on other electrical terminal points is apparent.

2.6.5 Fire, Toxic Fumes, and Operation in Hazardous Atmosphere

The requirements of the instrumentation system may involve operation in a hazardous or potentially hazardous environment. Such requirements preclude the more desirable alternative of avoiding these areas altogether. It is necessary, therefore, that all reasonable effort be made to achieve a design in which the possibility of failure, destruction, or personal injury in these areas is minimized.

2.6.5.1 Explosion Proof Components

Ensure that electrical components located in an area likely to contain flammable fluids or vapors from any source are explosion-proof. Explosion-proof aeronautical equipment is defined as that which, when operated at any design load, will not ignite an explosive mixture in the equipment or, if an explosion does occur within the equipment, this explosion will not cause any explosion or fire outside the equipment.

2.6.5.2 Combustible Materials

High-power electrical components may be potential ignition sources to solid combustibles or flammable fluids when resistance heating occurs due to a malfunction. Ensure that such components are not fabricated from combustible material and that they are located away from or shielded from combustibles. If possible, provide overheat protection if equipment case temperatures, in a failure mode, can approach the autogenous ignition temperature of the hazardous fluid. Ensure that the materials used in the specific equipment cannot combine with elements of the operating environment to form toxic, corrosive, or combustible fumes.

Likewise, design to avoid the possible liberation of fumes which degrade the performance of the equipment or endanger the operator's health.

2.6.6 Personnel and Equipment - Safety Relationships

During the development of the instrumentation system, give consideration to proper grounding, shielding, interlocks, safety guards, barriers, and warning markings. Minimize the hazards of electrical shock during routine maintenance; even small voltages can generate currents that are hazardous to health. Also, consider the limits of human strength in the various maintenance activities. When equipment is heavy, bulky, slippery, or unique in shape, provide mechanical guides, handholds, rails, slides, or other aids to make a safe and rapid installation or inspection.

2.6.6.1 Equipment Installation

Instrumentation equipment should be designed so that it cannot physically be installed improperly. Use proper connector keying, coded shapes, asymmetrical mounts, and other means to prevent inadvertent maintenance errors. Design for rapid positive identification of equipment malfunction and, further, for the rapid, positive identification of the replaceable defective assembly or component. Simple design which permits rapid isolation and repair of the faulty item reduces the possibility of creating additional damage during the troubleshooting process. Minimize the complexity of maintenance tasks by employing a simple design which includes interchangeability and standardized components. Reduce excessive maintenance time and possible electrical malfunctions as a result of loose or 1st hardware by employing captive components such as doors, covers, and fasteners where practicable. Whenever possible and practical eliminate the need for maintenance by using sealed components, self-adjusting, self-compensating, and self-calibrating equipment.

Provide for equipment cooling to maintain the required performance, life, and reliability of components under any probable combination of service conditions. Where louvers or vents are used, provide filters or screens at such points to prevent dust and insects from entering the equipment housing. Locate or configure vents to prevent foreign objects from being inadvertently inserted and contacting high-voltage points.

2.6.6.2 Mechanical Considerations

Avoid sharp projections on cabinets, doors, and similar parts. Ensure that doors or hinged covers are rounded at the corners and are provided with stops to hold them open. Include provisions to prevent accidental pulling out of drawers or rack-mounted equipment components which could cause equipment damage and injury to personnel. Design and locate critical switches and similar controls so that accidental contact by personnel will not place equipment in operation. Provide positive means to prevent the inadvertent reversing or mismatching of instrument leads and electrical connections. Color code or mark components to prevent mismatching only when more positive and foolproof means are not feasible in the design.

2.6.6.3 Batteries

Ensure that battery connections are made with reliable, sealed electrical connections. Vent lead acid batteries to an area where ignition is not possible. Provide nickel cadmium batteries with pressure relief vents, and hermetically sealed batteries, where used, with adequate safety blowout plugs. Ensure that all vent lines, fittings, etc., are resistant to decomposition by the battery electrolyte. Under no circumstances will batteries be located in crew compartments.

2.6.6.4 Lightning Protection

The metallic shell of the aircraft usually provides adequate protection against lightning strikes; however, the design should be thoroughly tested for lightning susceptibility. The use of adequate bonding techniques to ensure a direct and omnidirectional path for current across junctions or openings in the skin will prevent possible vapor ignition from electric arcs across such junctions.

2.6.6.5 Hazardous Instrumentation

Experience has indicated that designing safety features into systems is a more effective way to reduce accidents than campaigning to make humans more safety conscious. Not all hazards are of equal magnitude or criticality to personnel safety and quite often the most insidious hazards are those with which we are all familiar. In these areas, familiarity often breeds contempt. The instrumentation engineer is often confronted with hazardous instrumentation and he may or may not be familiar with established operational procedures.

2.6.6.5.1 RF Radiation Hazards To Personnel

It is well established that microwave (RF) radiation can lead to biological damage to humans because of the heating effects which result from the absorption of microwave energy by the body. Specifically, the eyes and testes are known to be more susceptible to microwave radiation than other parts of the body.

The entire topic of biological damage effects of RF radiation is quite controversial. In most cases standards have not been established in the lower frequency bands and operating guides presently used have been determined as a result of analytical studies. The disparities at the higher frequencies generally reflect a basic difference in the experimental approach. Accordingly, "recommended maximum" levels of human exposure to RF radiation have been established. One such guide is summarized in Figure 2.6-1. The guide relates to situations where accidental exposure occurs rather than deliberate or medically controlled exposures. The guide further assumes that deviation from normal conditions can take place ...with caution. Ref. (F5).

The limits of deviation from normal conditions are shown in Figure 2.6-1 as dashed lines.

The generally accepted safe level for incident electromagnetic energy of frequencies from 10MHz to 100GHz has been set at 10 mW/cm², average over any possible 0.1 hour period. This exposure level is shown in Figure 2.6-1 and labeled as "caution zone".

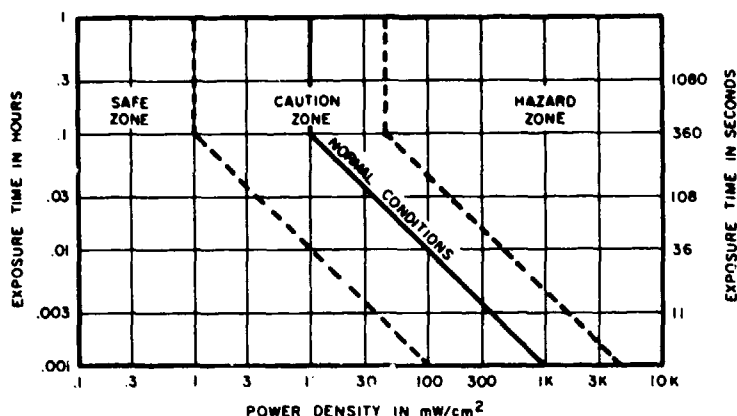


Figure 2.6-1 Electromagnetic Ambient Exposure Levels to Humans (Ref B5)

2.6.6.5.2 Laser Radiation Hazards

Laser systems are relatively new; however the number in use is increasing rapidly. All too often new systems are introduced into inventory only to discover that they are not safe; that is, they are hazardous to both personnel and equipment.

Laboratory experiments have proven conclusively that fast-pulsed lasers are considerably more hazardous than continuous wave lasers. Pulsed lasers in the nanosecond and faster time regimes can cause eye damage at relatively low average power levels. Accordingly, access controls and eye protection should be required if any exposure is possible.

3.0 SYSTEM INSTALLATION DESIGN MANAGEMENT

A safe and efficient instrumentation system begins with the installation design. Such factors as standardization of the system wiring, system components, and connectors will save installation time, weight, and cost.

Further, it is during the installation design phase that proper locations should be chosen for equipment and wire routing. (See Section 5.3) Once the actual installation phase begins, changes in equipment location and cable routing become very time consuming and costly.

In addition to the careful routing of the wiring and wire bundles, proper electrical grounding methods must also be established.

Shock/vibration requirements are often overlooked during the installation design phase. It must be remembered that isolation mounted equipments need additional space in which to be mounted, due to vertical and horizontal movement. This movement also requires additional cable and wiring lengths.

3.1 Interrelation of Systems

In order to produce a safe and efficient instrumentation system, the engineer must carefully design the installation interface. The mechanical and electrical interfaces must preserve the integrity of both aircraft and instrumentation systems.

3.1.1 Mechanical Interface

Mechanical interfaces include the installation of all the system components and their interconnecting cables. Each component must be carefully placed within the aircraft and fitted so that the possibility of mechanical interference of moving or free-to-move parts which could cause malfunction or damage is avoided. For example, shock/vibration mounted equipment is often quite free to move. In these circumstances, a full scale mock-up is very helpful.

3.1.2 Electrical Interface

With complex systems that are electrically powered there is always the possibility of creating designs in which power intended to actuate one component may be inadvertently applied to some other component. Whenever possible, it is a good practice to isolate electrical subsystems from each other. However, this is not always practical and electrical system design should be carefully reviewed for the latent sneak circuit. Also, there is the interface that exists between power generation or conversion equipment and their various electrical loads. It is possible that two different components do not have proper grounding or grounding isolation. Although sometimes difficult to simulate, electrical mockups can be a valuable tool in developing compatible electrical interfaces.

3.1.3 Electronic Interface

An aircraft is very often "over-loaded" with electronic equipment of various types. As a result, an instrumentation installation can experience serious problems due to ground loops, common-mode and other types of interference. Proper design may minimize this through isolation and shielding of sensitive wiring components. This procedure is best done during the development of the installation design. Even then, however, it is usually necessary to work with the final installation to reduce interference to an acceptable level.

3.1.4 Integrated Design

From the viewpoint of weight and performance, a high degree of integration (multi-purpose chassis) in the basic installation design looks like a good engineering practice. However, this type of approach should be carefully considered and connector interfaces kept to a minimum. Highly integrated systems not only require additional engineering and development but the design deficiencies do not usually appear until late in the installation and during the final integrated checkout. Further, integrated system checkout is more complex and usually expensive.

3.2 Design Management

Most instrumentation installations are one-of-a-kind and must be specifically designed for the particular application. The completed design effort is made up of many tasks that must be carefully coordinated. In order to properly manage the total effort, various controls must be levied on each effort. An effective means of accomplishing this is to standardize the majority of components, connectors, and wiring used. By using this technique, volume, weight, power, and reliability can be predicted.

3.2.1 Available Installation Space

Because the center of gravity of an aircraft is fixed within specific tolerances, the location of each piece of instrumentation equipment is important. Furthermore, there are certain items of equipment that can only be located in specific spaces or regions. Other items have preferred locations, but can be accommodated with some penalty elsewhere within the aircraft. Some of these problems of location are eased if the equipment is reduced in size. It is also efficient to install the various equipments closely together to minimize wasted space. This close packaging must be done carefully, however, to avoid arrangements that may complicate environmental and maintenance considerations.

In locating equipment, three-dimensional models or mock-ups are a valuable aid. If necessary, as the installation design develops, more sophisticated models or full-scale mock-ups can be constructed to solve some of the more difficult sizing problems. The closer together electrical units can be placed, the shorter the interconnecting wires will be, reducing both weight and volume.

3.2.2 Weight Control

Most project managers start with the preconceived idea that all instrumentation systems are overweight. If weight control is a problem, the standardization method of selecting the items to be installed will be very helpful. Although considerable progress has been made in miniaturizing electronic circuits, very little has been accomplished that would save weight in the installation hardware, such as wiring, connectors, circuit breakers, equipment isolation mounts, attachment clamps, and so forth. This is due primarily to the environmental requirements imposed on both the equipment and installation hardware.

Experience has shown that regardless of careful weight control planning, the estimated weight of the installation will gradually increase from the time that the project has started until it is concluded. Typically, a 25% increase in weight can be anticipated over a four to five year period. It would seem to be practical then to allow for this weight growth. Consider the following suggestions for minimizing the initial installation weight.

- a. Minimize redundant transducers and wiring.
- b. Minimize the use of individually shielded wiring by using multi-conductor cabling with a common shield.
- c. Shield the interference source rather than each affected wire.
- d. Use crimp connectors rather than soldered connectors and whenever possible, use modular terminal blocks.
- e. Minimize wire and cable lengths by careful equipment installation planning.
- f. Although wiring that uses aluminum conductors would be a great savings in weight, its use is not recommended. (See Section 4.6.4.3.5).

These suggestions are derived from a generalized instrumentation installation. It must be assumed that the selected components that comprise the data acquisition system reflect a minimum total weight.

3.3 Instrumentation Installation Diagrams

The development of an instrumentation wiring diagram is basically the methodology of installing and routing individual wires and forming them into a wire bundle (or harness). Installation methods are well controlled by a wide variety of procedures and specifications that dictate specifics. Accordingly, these details will not be repeated in this section. However, careful and thoughtful planning is required to develop a good installation. For example, careful selection of connector shape and size, connector contact assignments and standardized connector patterns can simplify system installation design, improve system reliability and ease inspection. Refs. (12, 13).

3.3.1 The Block Diagram

The basic simplicity of the block diagram makes it an excellent choice for presenting the related functions of a complex system. Such a diagram can show the normal order of progression of a transducer signal for example, from its origin to its final destination. In general a block, in a block diagram, represents one of two things: (1) it may represent a space, component, or item of equipment; or (2) it may indicate a system within any of those items mentioned in (1) above.

For example, a block diagram may be used to represent the idea of an instrumentation system as shown in Figure 3.3-1. In this example each block represents removable components.

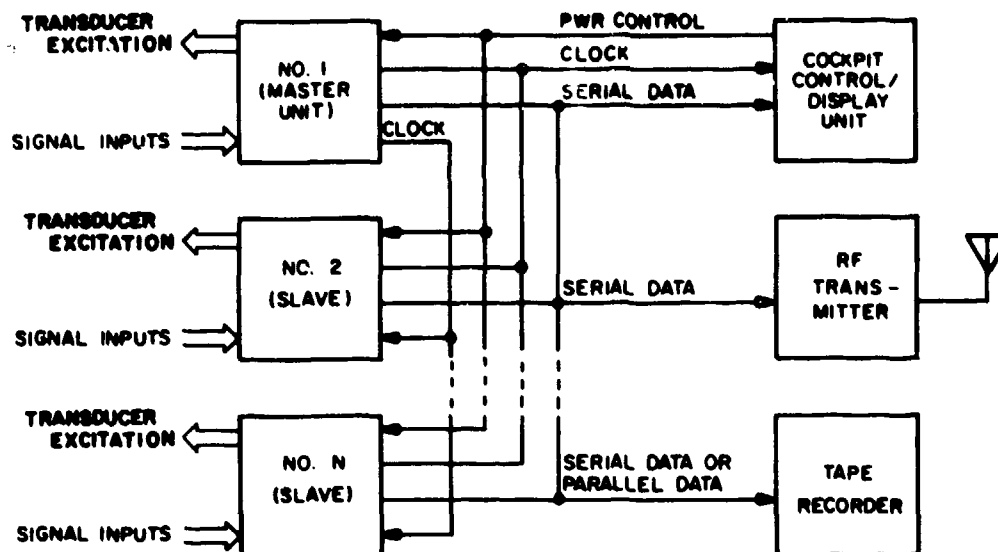


Figure 3.3-1 Block Diagram Representing the Concept of an Instrumentation System.

In Figure 3.3-2 the block diagram is used to facilitate an understanding of the internal electronics of a transducer power supply.

The instrumentation engineer must carefully determine the contents of the block diagram since it is usually the basis for a wiring diagram. In general, the block diagram should be kept simple and uncluttered. To achieve this goal the instrumentation engineer should limit the block diagram to as few unrelated functions as possible. For example, if the block diagram has been drawn to show transducer signal paths, do not include power distribution paths unless the power distribution path is so simple that adding it does not clutter up the layout.

The following suggestions are offered as an assistance in developing a block diagram.

1. The block diagram is often the basis from which the wiring diagram will be drawn. Use the block diagram as a simple and accurate reference for drawing the wiring diagram.

2. Categorize the information to be shown and draw as many diagrams as may be required. For example, wiring can be categorized as suggested in Section 5.4.1. The block diagrams may be combined in accordance with the rules governing the wiring categories.

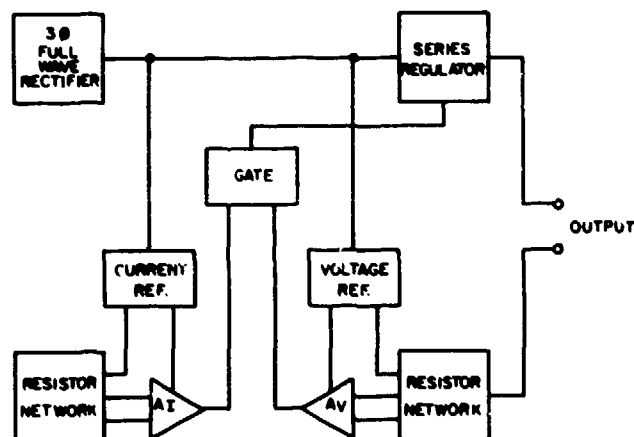


Figure 3.3-2 Block Diagram of the Electronics of a Transducer Power Supply Output.

3. The block diagram should be drawn so that functions progress from left to right as shown in Figure 3.3-3.
4. The block diagram as drawn should be limited to squares, rectangles and triangles. Rectangles or triangles may be used for amplifiers as shown in Figures 3.3-4 and 3.3-5.
5. The dimensions of the squares, rectangles and triangles should be kept as uniform as possible. However, their size is not fixed, since the size has no bearing on their importance.
6. A single heavy line should be used to show the path of signal progression from block to block.
7. Arrowheads should be used on the signal path to indicate the direction of signal progression, see Figure 3.3-4.
8. Some paths terminate at components, such as antennas, and these components should be shown by means of their standard graphic symbols rather than by blocks.
9. If power distribution components are shown in the same block diagram as signal sources, the power path lines should be of a lighter weight.

- For clarity of the diagram, do not use arrowheads on the power flow path lines.
10. Descriptions of the components shown should be placed within the blocks.
 11. If possible, show the location for each component. Use dotted lines for separation and label each location (Figure 3.3-5).

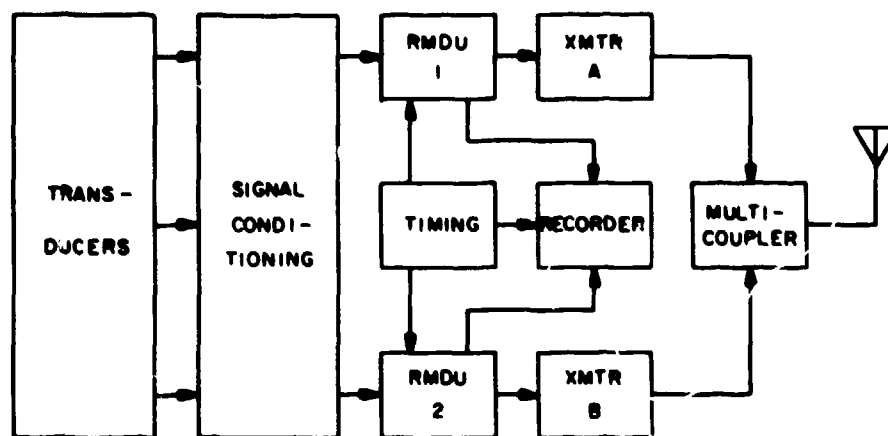


Figure 3.3-3 Example, Block Diagram

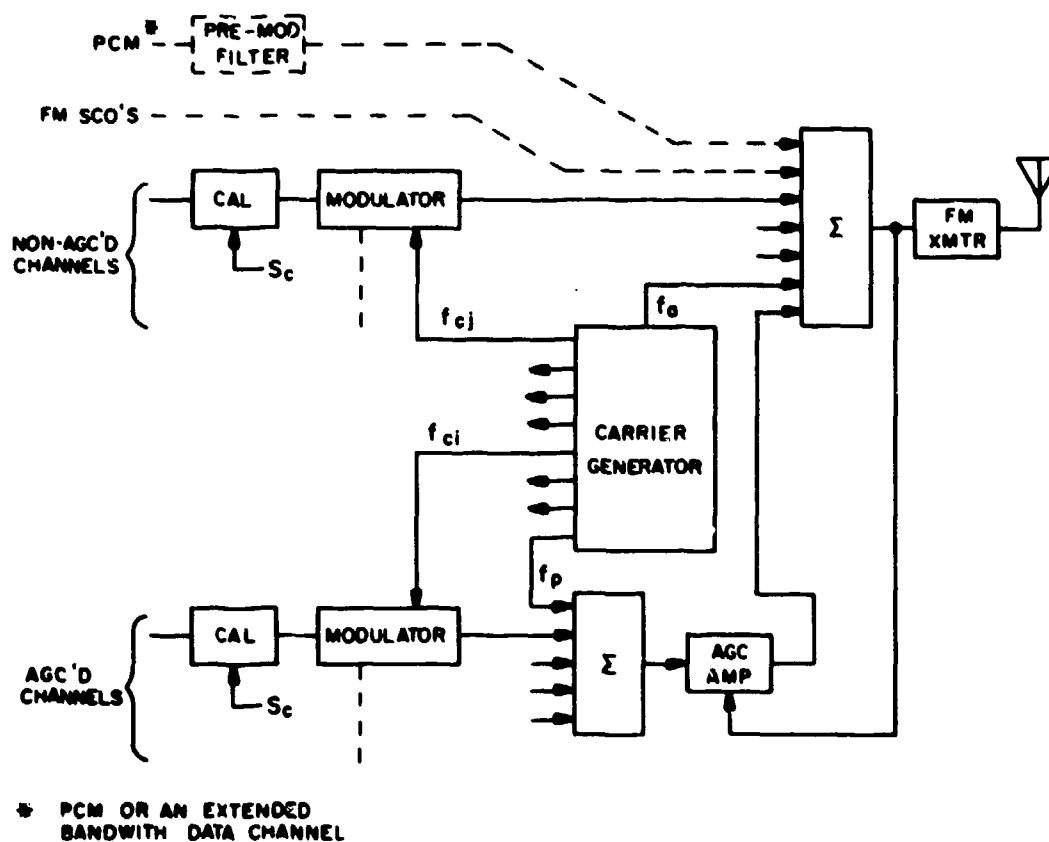


Figure 3.3-4 Example, Block Diagram

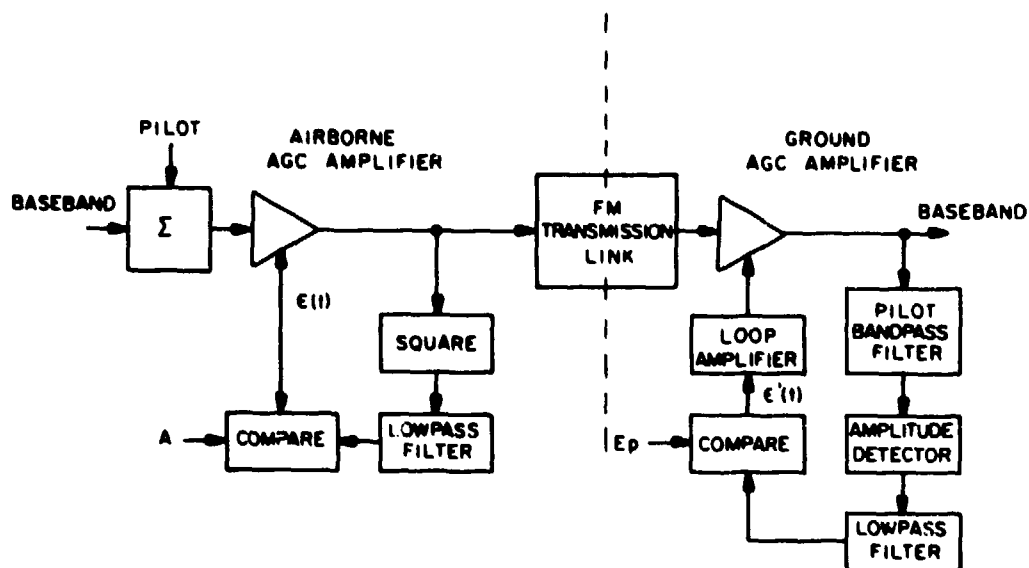


Figure 3.3-5 Example, Block Diagram

The suggestions listed above reflect the routine procedures for preparing a block diagram. Beyond these suggestions, the block diagram may take on any form.

3.3.2 Connection Diagrams

In many areas of the electrical industry, the older term "wiring diagram" has been replaced by the newer term "connection diagram." At present, however, both terms are still used interchangeably. The following discussion will use the terms interchangeably as suitable.

The different types of wiring or connection diagrams may be classified according to their general layout as follows:

1. Point to point interconnect diagram.
2. Highway or trunkline diagram.
3. Block interconnect diagram.
4. Schematic diagram.

3.3.2.1 Point to Point Interconnect Diagram

In this type of diagram each wire is drawn from one component to the next; to connectors, terminals, and equipment. The wires are routed as direct as possible and are generally drawn in vertical and horizontal directions as shown in Figure 3.3-6.

Each wire, connector, contact, and component is carefully identified. The components and equipments are identified by appropriate symbols, abbreviations, or short functional titles. This type of diagram is often used in the installation of add-on systems. Each connection must be carefully identified so that it can be located within the existing instrumentation installation.

3.3.2.2 Highway or Trunkline Inter-Connect Diagram

This type of drawing differs from the point to point style in that

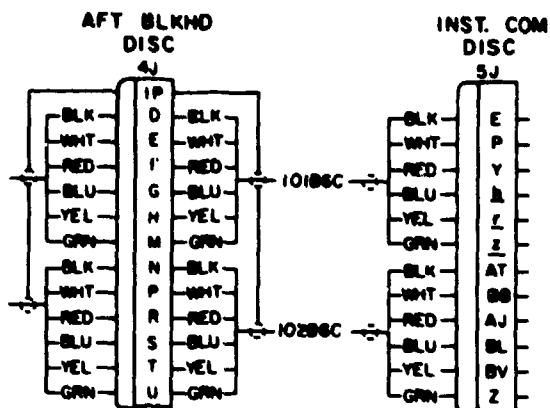


Figure 3.3-6 Point to Point Inter-Connect Diagram.

the wires are merged, or joined, into long single lines often called "highways" or "trunklines." This drawing technique is shown in Figure 3.3-7. These highways or trunklines do not necessarily conform to any specific bundles or harness. The choice is usually left to the instrumentation engineer. The example in Figure 3.3-7 does not show any harness identification; therefore, the trunkline technique was used to save drawing time and space and not to provide wiring harness information.

3.3.2.3 The Block Inter-Connection Diagram

The block interconnection diagram is a combination of the block diagram and the trunkline diagram. Its purpose is to provide equipment connector identification and wiring harness grouping, wiring harness routing, and relative equipment location. An example of a typical block interconnection diagram is shown in Figure 3.3-8. A portion of Figure 3.3-7 is included.

The block interconnection diagram can be used as a guideline for instrumentation harness development and installation.

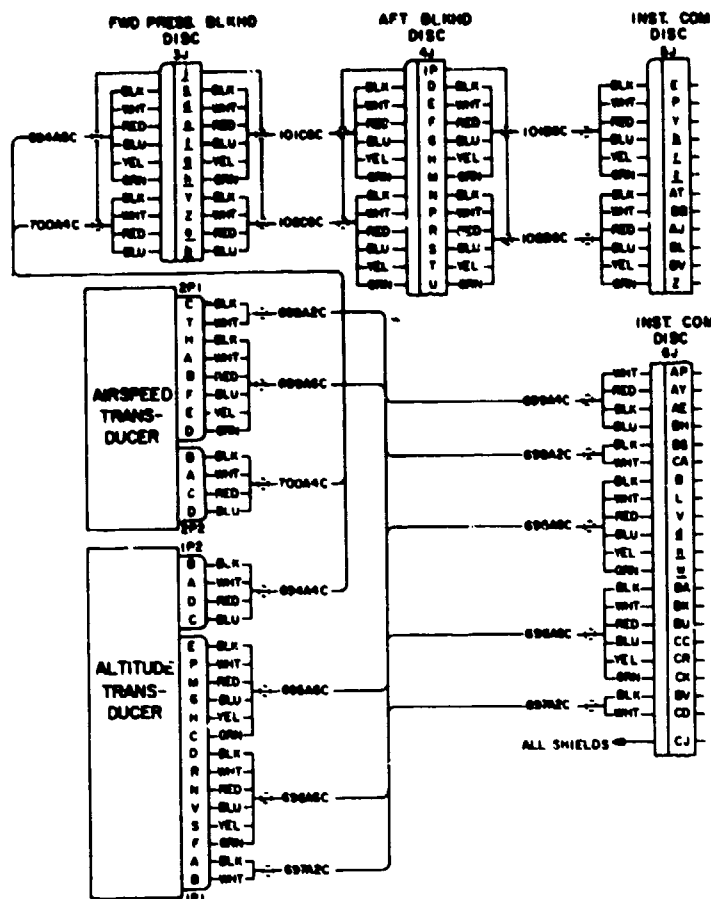


Figure 3.3-7 Highway or Trunkline Diagram.

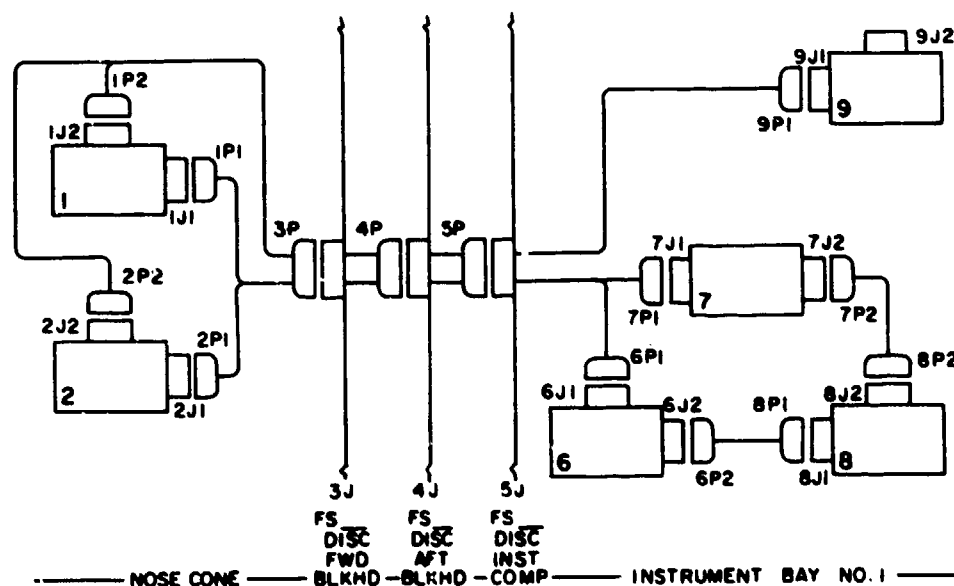


Figure 3.3-8 Block Interconnection Diagram

3.3.3 The Schematic Diagram

A schematic diagram shows the connections and the functions of a circuit arrangement by use of graphic symbols. The diagram does not show the physical relationships of the components within a circuit. Several examples are shown in Figure 3.3-9. Six strain gages are shown along the left hand edge of the diagram, items (A) through (F). This combination of schematic diagram and point to point diagram is often used to clarify the operation of transducers during installation checkout and during trouble-shooting. Observe that (A) has been annotated to indicate the excitation and signal wiring polarity.

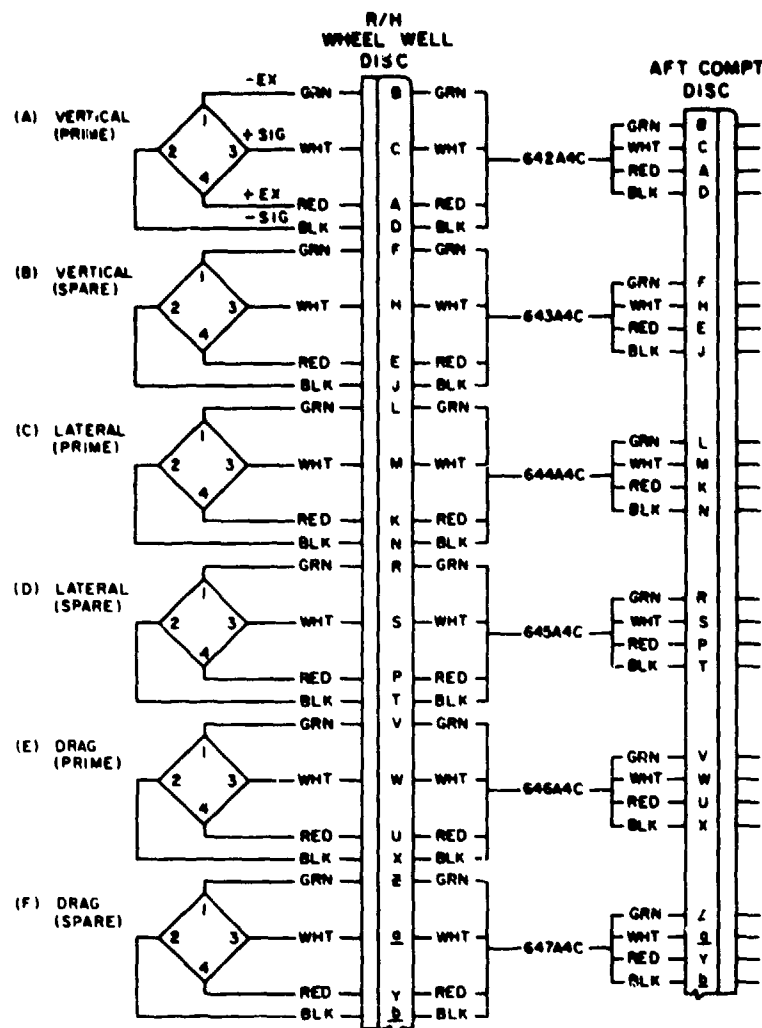


Figure 3.3-9 Use of the Schematic Diagram
as a Part of the Point to Point Diagram

3.3.4 Instrumentation System Wiring Diagrams

The wiring diagram is the beginning of a very complex process. The release of the final wiring diagrams to the aircraft instrumentation technicians will implement all of the choices and decisions made during the installation design phase. These choices and decisions can be made easier, however, if careful preparations are made prior to drawing the final instrumentation diagrams. Accordingly, the following discussion presents several wire routing procedures that can assist the instrumentation engineer in optimizing the installation wiring diagram.

3.3.4.1 Preliminary Preparations

For purposes of this discussion it must be assumed that the instrumentation engineer has a finalized measurement requirements list in his possession. This listing contains all of the required parameters, their range and total number of transducers required.

The instrumentation engineer should inspect the aircraft as early into the program as possible (see Section 2.1 also). The following examples will illustrate the necessity for becoming familiar with the aircraft.

- Environmental conditions** - It is not uncommon for instrumentation wiring and components to be located in a hostile environment. The temperature, vibration, and pressure ranges of areas designed for instrumentation use must be clearly understood. Extreme environments require special (and costly) wiring and components.
- Available space** - The space available for the installation of instrumentation wiring and components often determines instrumentation size and installation methods. Access to these areas may require special packaging and/or connectors. This is particularly true of the smaller aircraft such as the fighter class.

- c. Wiring and cable routing possibilities - Wire and cable routing is dependent upon the location of each part of the instrumentation system. The location of pressurized compartments and structural limitations can affect connector or lightening hole size which in turn will affect maximum harness size. Indirect wire routings will also increase the possibilities of unacceptable voltage drops due to excessive wire lengths.

Following the aircraft inspection the instrumentation engineer should have a better understanding of those requirements unique to the instrumentation installation. The majority of the instrumentation systems transducers and system components can now be identified in a block interconnection diagram.

3.3.4.2 Component Standardization

For most applications the instrumentation system installation will use a large number of in-house components. Standard components such as recorders, transmitters, signal conditioners, power supplies, transducers, time code generators, fuse boxes, and power distribution panels are typical examples. The importance of the phrase "standard components" must not be overlooked. Each of these components has been thoroughly tested and operationally proven. Their adaptability to a new aircraft installation is a known factor. More important, however, is the previous experience gained by using the "standard component." Its size, weight, and wiring hook-up are well known and most important installation hardware is usually available from in-house supplies.

Using the identical component in a variety of instrumentation system installations is a basic form of standardization. Since each of these components is physically mounted and electrically wired in a similar manner, the installations are simplified for the technician.

3.3.4.2.1 Transducer and Connector Standardization

Transducers and connectors are probably the best examples of components that benefit from standardization. Standardization can minimize installation time and facilitate maintainability. Figure 3.3-10 depicts several examples of in-house transducers standardized to conform to a four-conductor color coded cable. Whenever possible or practical the attached connector should be standardized so that uniformity of color, pattern, and circuit function exist.

Standardization makes the task of drawing the wiring diagram easier and minimizes the opportunities of making a mistake.

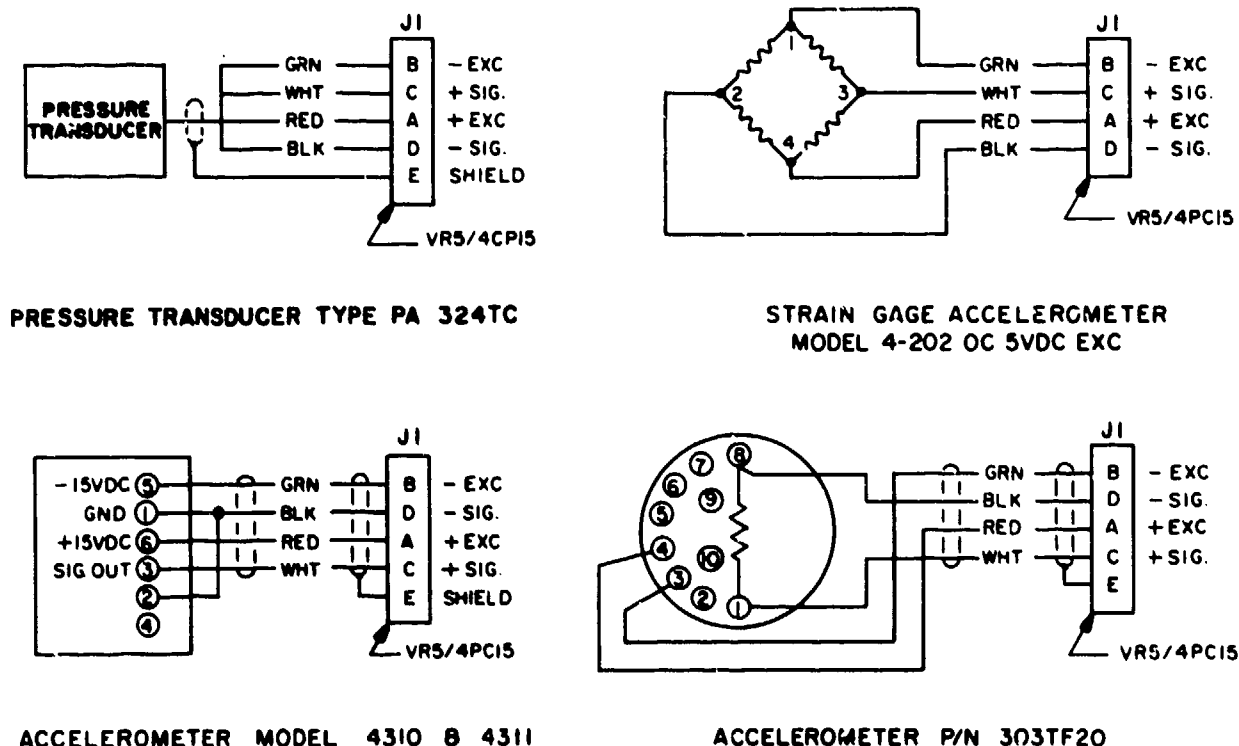


Figure 3.3-10 Transducers With Standardized Connectors

Figure 3.3-9 is an example of transducer concentration in an area that requires a wheel-well disconnect and an intervening connector at the aft compartment.

The wheel-well disconnect is a 50 contact rectangular connector. The instrumentation engineer can arbitrarily assign the connector contacts as shown in Figure 3.3-11. Assuming that the mating half of the connector is wired accordingly, the diagram if implemented will provide trouble free operation. However, before power is applied and the circuit functionally tested, it must be inspected by the technician and the electrical/electronic inspector. Using Figure 3.3-11 the inspector will have to follow each color from each four-wire cable to its respective contact. An arbitrary selection scatters the four colors throughout the connector. Figure 3.3-12 shows the same connector with the four colors routed to carefully selected contacts. The colors as shown in Figure 3.3-13 are uniformly placed in columns, one cable for every two horizontal rows. The shields can be routed through on contacts set aside for that purpose.

The same wiring procedure can be applied to the aft compartment disconnect which is in this example a 104 contact connector with the contact pattern shown in Figure 3.3-14. This example shows the 104 contact connector using a contact identification similar to that of Figure 3.3-12.

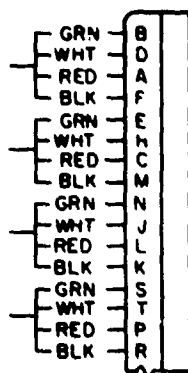


Figure 3.3-11 Arbitrary Contact Selection

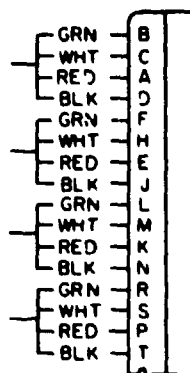


Figure 3.3-12 Planned Selection of Contacts

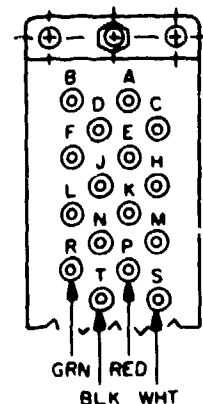


Figure 3.3-13 Colors Aligned As Wired in Figure 3.3-12.

Whenever possible, if all rectangular connectors are wired as shown in Figure 3.3-12 the task of drawing the diagram and installing the contacts is made much easier.

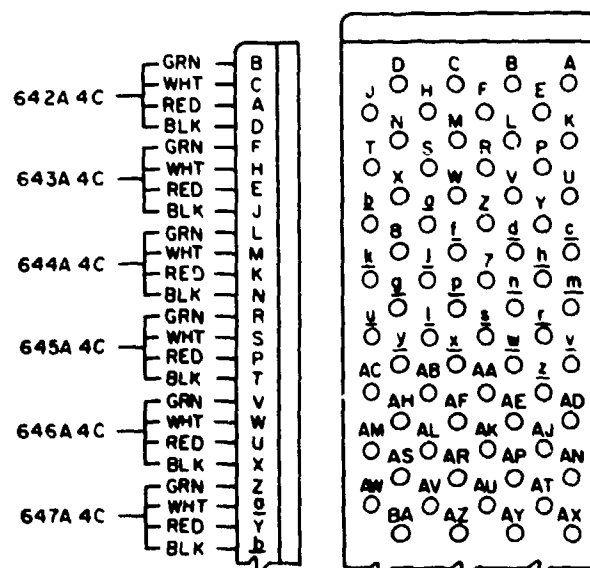


Figure 3.3-14 104 Contact Connector, Aft Compartment Disconnect

3.3.4.2.2 In-House Designed Instrumentation Equipment

The standardization concept of color coding and connector contact assignment can also be applied to the instrumentation equipment designed and constructed in house.

Signal conditioning equipment is probably the best example of instrumentation equipment built in house. Figure 3.3-15 shows portions of the input connectors to an eighty channel signal conditioning box.

Channel 1 at connector J1 shows the wiring pattern to be +EXC (A), -EXC (B), +SIG (C), -SIG (D).

Referring back to Figure 3.3-10 and using the standardized four conductor colors, red (+EXC), green (-EXC), white (+SIG), black (-SIG), J1, J2, and J3 will be wired as shown in Figure 3.3-16. Several contacts in each connector were reserved for a shield bus and spares.

As before, the drawing is standardized and errors in wiring can be more easily detected.

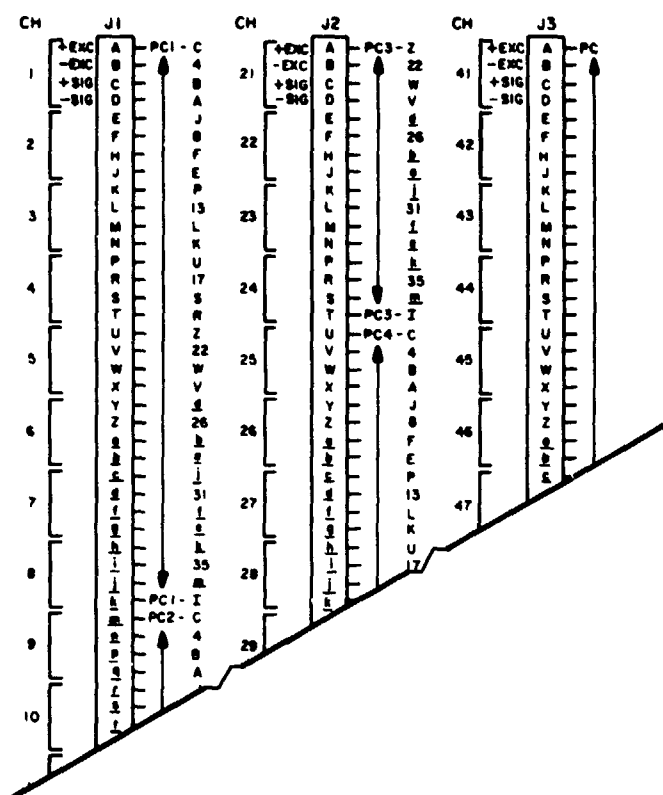


Figure 3.3-15 Excitation/Signal Polarity Assignment at the Signal Conditioner Input Connector.

The output connectors J5 and J6 of the signal conditioning box are wired as shown in Figure 3.3-17. The output signal polarity is shown at channel 1. All other channels are wired accordingly.

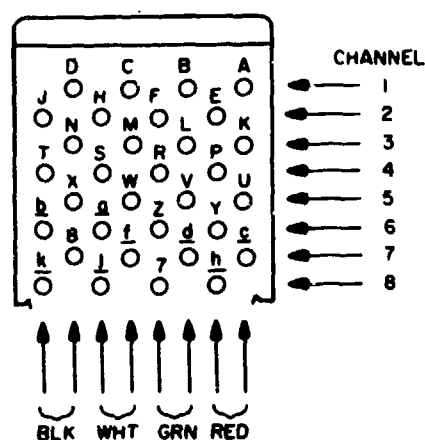


Figure 3.3-16 Color Pattern on the Signal Conditioning Input Connectors, J1, J2, and J3

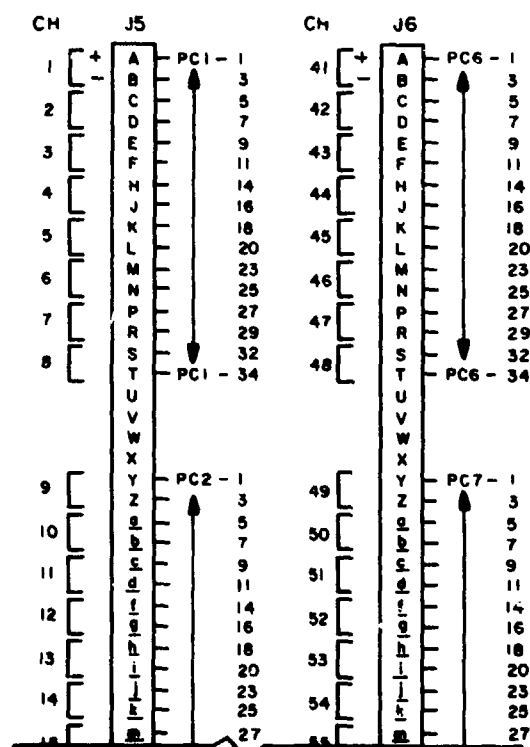


Figure 3.3-17 Output Signal Polarity Assignment at the Signal Conditioner Output Connector

Using the standardized wiring colors shown in Figure 3.3-13, the output connector color pattern should conform to Figure 3.3-18.

Although the above examples relate only to the signal conditioning chassis, the same standardizing philosophy should be applied to all wiring connections. Above all, be consistent because in being consistent the instrumentation drawings are predictable. Predictability is a valuable aid in troubleshooting installation drawing and wiring errors.

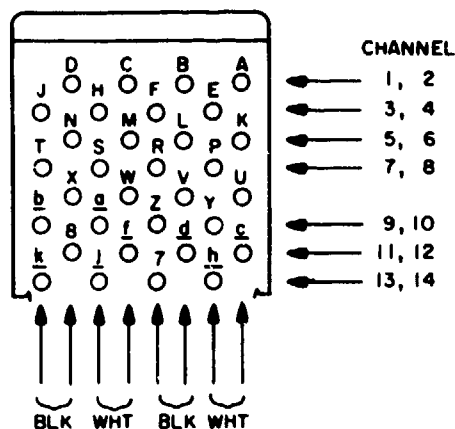


Figure 3.3-18 Color Pattern on the Signal Conditioning Output Connectors, J5 and J6.

3.4 Instrumentation Subsystem Compatibility

When considering the compatibility of a subsystem with the electromagnetic environment, both conducted and radiated interference must be considered. However, for purposes of this discussion it is assumed that the instrumentation engineer is responsible only for the conducted interference since this is a factor within the scope of the installation design and under his control.

The operational capabilities of electrical and electronic subsystems require that data signals be free of interference (noise). The introduction of noise into the subsystem can result in loss of data or as a minimum degrade the overall subsystem operational quality. Careful installation methods are required in order to insure low susceptibility, particularly to low frequency transients and 400 Hz induction fields. Ref. (14, 15, 16)(B3).

The material presented here provides basic suggestions for eliminating some of the more common problems encountered in noise control.

3.4.1 Interference Coupling at Low Frequencies

Wires which are close to each other may couple energy from high level wiring circuitry to low level wiring circuitry by induction field coupling. This is a near field coupling phenomenon and is divided into magnetic and electric field coupling. These wiring circuits may be located in the same wire harness or near each other in separate harnesses. Low frequency coupling is considered to occur with wire lengths one-sixteenth of a wavelength or lower, as related to the interference frequency. (See Section 3.4.3.2).

3.4.1.1 Magnetic-Field (Inductive) Coupling

Interference voltages are induced into the wire by flux linkage originating from an adjacent source. The source of interference will be a generator of magnetic flux which may be a transformer, a solenoid, or in most cases a current carrying wire. The voltage induced into an adjacent wire or loop by a parallel wire of infinite length and carrying a current is diagrammatically shown in Figure 3.4-1, and mathematically expressed in Eq. (3.4-1).

$$E = (1.257 \times 10^{-6}) f L I \ln \frac{r_2}{r_1} \quad \text{Eq. (3.4-1)}$$

where E = induced voltage, volts

f = frequency, Hz

L = length, meters

I = current, amperes

r_1 and r_2 = loop spacing,

μ = permeability of the transfer

medium = 1.257×10^{-6} Henrys/meter

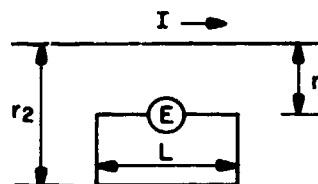


Figure 3.4-1 Voltage Induced in a Loop

If the susceptible loop is at an angle rather than parallel to the interference source, then some lesser value of E will result.

The significance of Eq. (3.4-1) is readily apparent. The induced voltage, E , increases with the permeability of the transfer media, μ ; line length, L ; loop size, r ; interference current, I ; and frequency, f . It decreases with separation of the wires, r_1 . The equation implies that the magnetic-field-induced voltage would continue to increase with an increase in frequency. However, the self inductance in the wiring circuit prevents this. Use Eq. (3.4-1) for low frequency coupling only.

3.4.1.1.1 Coupling Reduction Methods

To reduce the potential effects of the magnetically coupled interference, further examination of Eq. (3.4-1) and Figure 3.4-1 will be helpful. Figure 3.4-1 as shown presents the worst case condition consisting of a very large loop area due to the parallel wire circuitry. Thus, for the conditions shown, the following steps can be taken to reduce the coupling interference:

- Reduce the value of I in the source circuit.
- Reduce the effective loop area by reducing the loop length, L .
- Decrease the loop area by increasing the loop separation, r_1 .
- Apply both (b) and (c) above. In general the value of L cannot be significantly reduced since it is presumed to be as short as possible. The greatest improvement results from increasing r_1 until the wire length is directly adjacent to the ground plane.

Use a dedicated ground return wire instead of the ground plane return. This method will avoid the common-mode impedance coupling problem. However, the subject of how and where to ground the circuit often arises. If grounding is required it should be done at one point only as discussed in Section 3.4.4. If both ends are grounded then the equivalent circuit shown in Figure 3.4-1 has been recreated with all its inherent problems.

In practice, purchased equipments often times ground their internal circuitry to their chassis enclosure which in turn is hard mounted to equipment racks and system ground. Since it is usually impractical to unground these internal circuits from their chassis, the ground loop can be avoided by using an isolation transformer at their input, thus isolating the circuitry from ground at that end.

By far the best practice is that of twisting the dedicated ground return wire with the original wire. The twist or transposition of a wire and its return is a very reliable technique for minimizing a difficult interference problem. Twisted pairs of wire are readily available for aircraft use. Then, finally, route the twisted pair close to the ground plane.

3.4.1.1.2 The Unshielded Wire Pair

Two wire pair configurations are shown in Figure 3.4.2. The upper signal circuit illustrates a signal wire pair being disrupted by the magnetic and electrical field from a source wire having an alternating voltage V_s and an alternating current I_s .

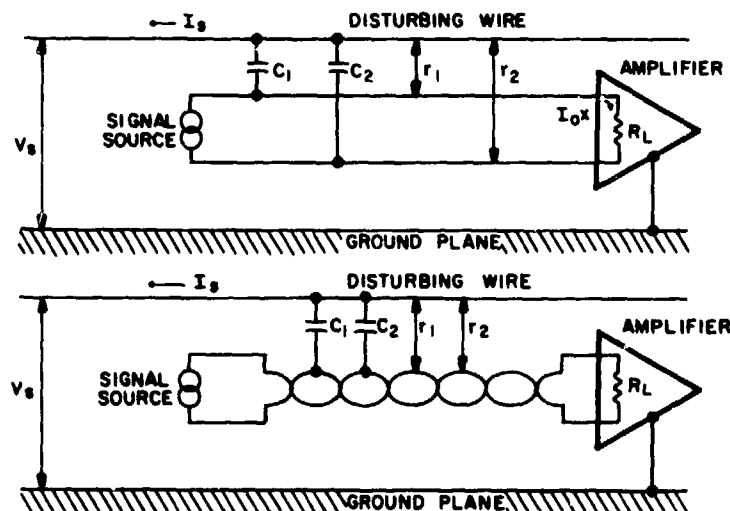


Figure 3.4-2 Operational Concept of the Twisted Wire Pair

The current I_s produces a magnetic field which cuts both wires of the signal circuit, thus inducing a voltage in the signal loop. The induced EMF is proportional to the magnitude and frequency of I_s and the area enclosed by the signal loop, but inversely proportional to r_1 and r_2 . (See Section 3.4.1.1). Since r_1 and r_2 are unequal, the distributed capacities C_1 and C_2 are also unequal. These related differences between $r_1 C_1$ and $r_2 C_2$ cause the electric field to produce a current I_x in the signal circuit which develops a noise voltage across the amplifier input resistance R_L .

If the two conductors in the signal circuit are transposed (twisted) at regular intervals, as shown in the lower part of Figure 3.4-2, then the distances r_1 and r_2 approach equality and the resultant loop area becomes very small. If the twist per unit length is uniform, then the loop areas tend to be equal, and the induced voltages, being equal and opposite, cancel each other. In addition, the twisting together of the signal pair has made C_1 and C_2 very close to equal values, thus reducing the effects of the electrical field so that shielding the twisted pair is less of a problem. (See Section 3.4.1.2)

A few additional comments regarding EMI-control for reducing magnetic coupling in wires and cables will be helpful in order to develop a better perspective of the problems normally confronted.

The above discussion implies that a twisted-wire pair is the best form of unshielded wiring to reduce magnetic coupling. There are exceptions; for example, the equivalent return wire for a coaxial cable is its outer shield. Since this shield is located around the inner conductor, its geometric location is concentric with the inner conductor. But since the outgoing wire is also located here, the effective distance to the ground plane is zero. This could be interpreted as saying that a coaxial cable provides better magnetic field isolation than a twisted pair. In actuality, the better of the two can be determined from (1) the extent of the magnetic-field gradient and (2) the uniformity of the twisted pair as compared to the coaxial cable. In both of these requirements, if the twisted pair has highly uniform twists per increment of length and the required total twists over the total wire length, then it should perform better than a coaxial cable. The coupling rejection offered by a uniformly twisted wire-pair is shown in Figure 3.4-3.

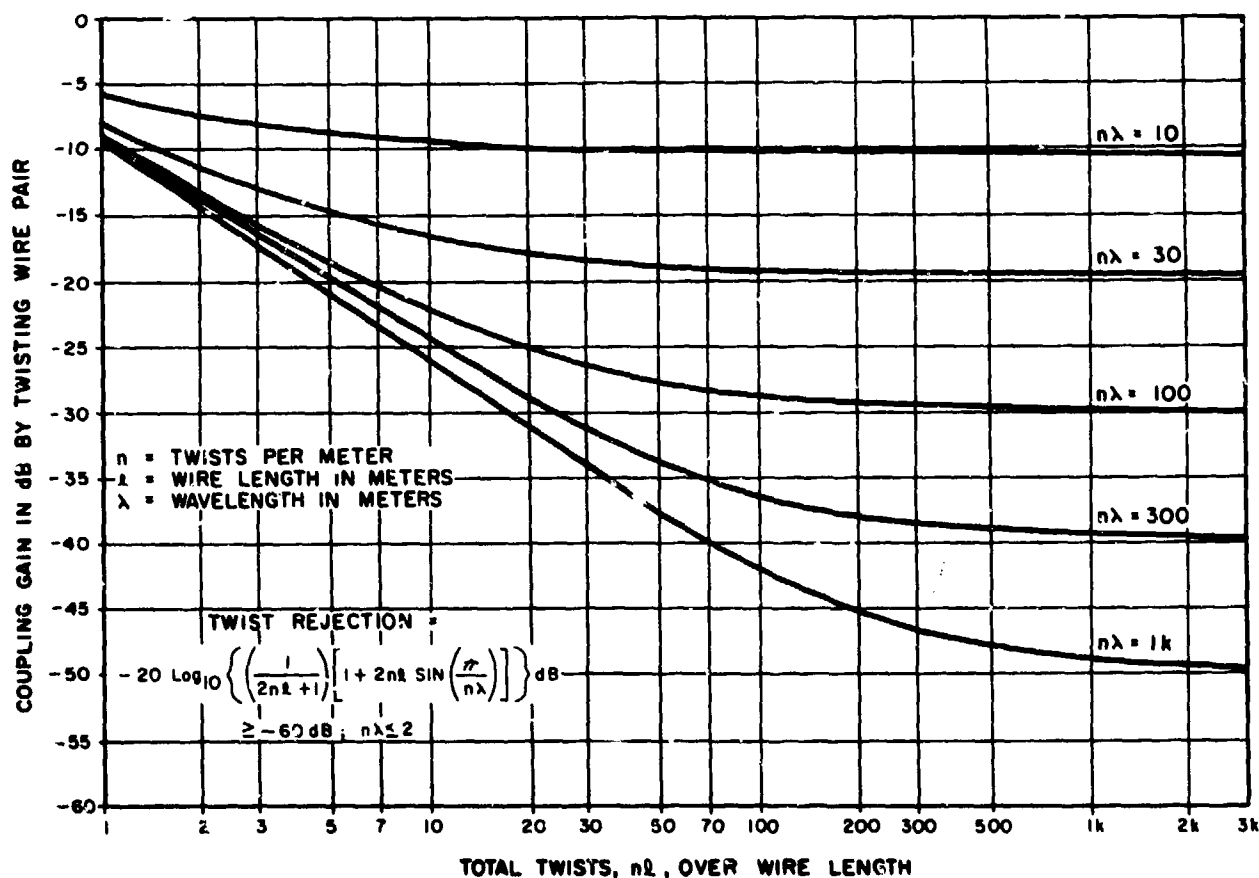


Figure 3.4-3 Coupling Gain Offered by a Twisted Wire Pair. Ref. (B5).

3.4.1.1.3 Shielding a Cable from the Effects of a Magnetic Field

The usual shields used on shielded wiring do not provide significant protection against magnetic coupling at low frequencies. However, there are two methods of reducing magnetic interference coupling which are associated with shielding: (1) magnetic flux from its source may be isolated from the pick-up loop by high permeability materials or (2) the magnetic flux may be directed away from a pick-up loop by high conductivity materials. Recent developments in cable shielding have made available braided shields that provide 20 dB attenuation at 400 Hz with minimum penalties of weight and flexibility.

High permeability materials restrict the flux leakage path from magnetic components such as transformers and may also be used to enclose susceptible wiring. High permeability tape has been used successfully to contain magnetic interference from long lengths of power transmission cabling. (See Section 5.4.8.3).

Loop Orientation - Coupling between the source and pick-up loop is reduced to a minimum when the conductors are perpendicular to each other. However, crossing cables at right angles in an aerospace vehicle is not always feasible.

3.4.1.2 Electric-Field (Capacitive) Coupling

In long cable runs, an appreciable capacitance can exist between adjacent wires and from each wire to their shield or to the aircraft ground plane. Additional capacitance will exist at connectors and in the wire bundle. The voltage induced into a wire from an adjacent wire is a function of these capacitances. Figure 3.4-4 illustrates one concept of capacitive coupling between two adjacent wires. Ref. (B3).

Referring to Figure 3.4-4, the interfering voltage E_o couples through the stray coupling capacitance C_c to produce a voltage E_x on the adjacent wire. Both wires have stray capacitance to ground as shown by C_a and C_b . Each wire is also shown with its system load impedances Z_1 , Z_2 , Z_3 and Z_4 . The stray capacitances C_a and C_b are in parallel with their load impedances. An equivalent diagram is shown in figure 3.4-5.

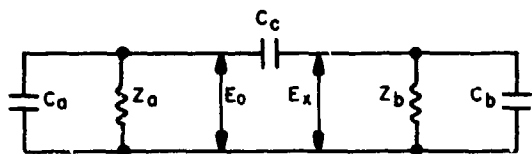


Figure 3.4-4 Capacitive Coupling Between Two Wires

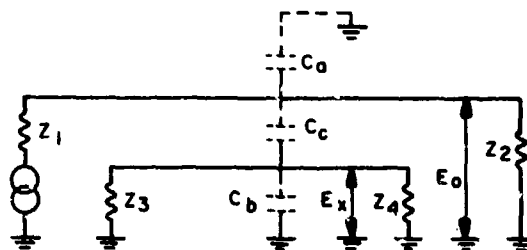


Figure 3.4-5 Equivalent Circuit of the Capacitance Coupling Shown in Figure 3.4-4

If the cable load impedances are very high, the frequency spectra of the voltages E_o and E_x may be affected by C_c and C_b . For example, the voltage ratio E_x/E_o as derived from Figure 3.4-5 is,

$$\frac{E_x}{E_o} = \frac{Z_x Z_b / (Z_x + Z_b)}{Z_c + Z_x Z_b / (Z_x + Z_b)} \quad \text{Eq. (3.4-2)}$$

as suggested, if Z_x is a high resistance load R_x , then

$$\frac{E_x}{E_o} = \frac{C_c}{C_c + C_b} \sqrt{\frac{R_x^2}{R_x^2 + \left[\frac{1}{2\pi f(C_c + C_b)} \right]^2}} \quad \text{Eq. (3.4-3)}$$

A plot of this ratio against $Z_x = R_x$ is linear until the reactance of $C_c + C_b$ is approached by R_x , after which the ratio asymptotically approaches a value equal to $C_c/(C_c + C_b)$.

The plot of E_x/E_0 against frequency will have the characteristic shape shown in Figure 3.4-6 for $Z_x = R_x$. When Z_x contains inductive reactance, resonances may cause variations in coupling with frequency. Such effects are most likely to occur at higher frequencies. When Z_x contains capacitive reactance, it is equivalent to an increase in C_b .

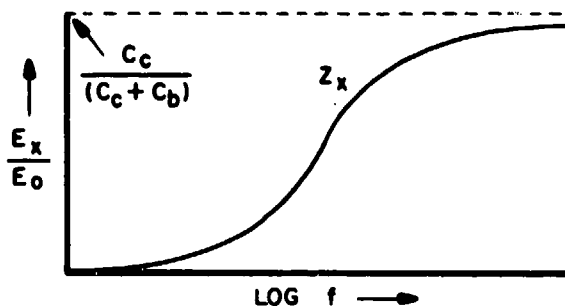


Figure 3.4-6 E_x/E_0 Plotted Against Frequency

3.4.1.2.1 Reducing Capacitive Coupling

The coupling capacitance C_c can be reduced by increasing the wire separation, using a shorter length of wiring or by shortening either wire in the bundle. When shielding is used on the sensitive wire, a large increase in C_b occurs as well as a reduction in C_c . The shield needs to be grounded at only one end to prevent any low frequency interference.

An alternate but less satisfactory method of increasing C_b and decreasing C_c is to reroute the sensitive wire with wires that do not carry interference signals. This is an effective technique if it is applied during the installation design phase. (See Section 5.4.1).

Lowering the input impedance Z_x in the sensitive circuit is a very effective way to reduce C_c if it can be done by circuit design. The value of Z_x must be carefully controlled, however, because low impedance at both ends of the circuit may contribute to magnetic coupling.

Another method by which interference may be cancelled out of sensitive wiring is through the use of balanced lines fed by balanced circuits. The signal wire and its return are maintained at the signal potential with respect to each other and are equally balanced between the ground potential. The coupled interference voltage appears equally on both wires, 180° out of phase, thus canceling the interference. Two-wire shielded cable can be used to reduce this type of interference coupling (see Section 5.4.4).

3.4.1.2.2 Capacitance Between Wires

The capacitance between unshielded parallel wiring is shown in Figure 3.4-7 for two configurations: two wires and a center conductor surrounded by six others (see Section 4.6.4.2). The capacitance between parallel unshielded and shielded wiring, for long lengths can exceed the limitations for many circuits; for example, a very high speed digital sampling circuit can be compromised by excessive transducer wire capacitance. In either case, shielded or unshielded, standard coaxial cable can be used to limit this impedance.

Wire and cable manufacturers quite often neglect to include the capacitance per unit length of their wiring when printing their brochures; therefore, Figures 3.4-7 and 3.4-8 have been included to provide typical shielded wire capacitance information.

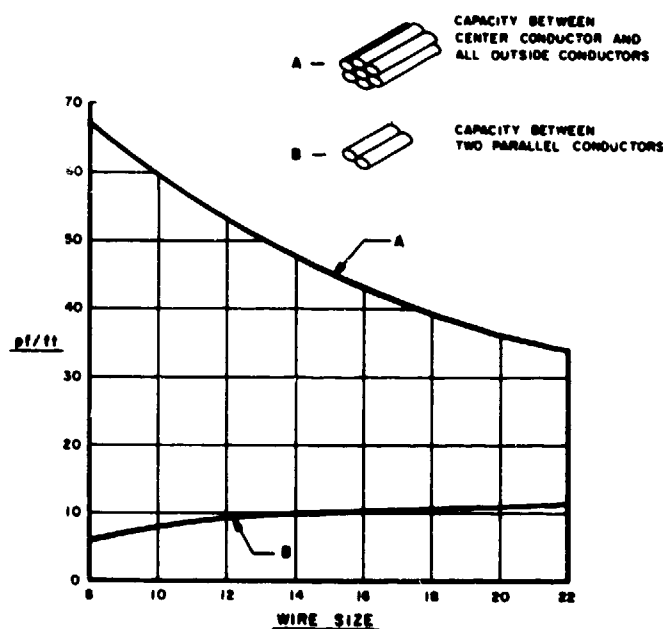


Figure 3.4-7 Capacitance vs Wire Gage for Cables of Two and Seven Unshielded Wires.

CAPACITANCE IN PICOFARAD PER FOOT (30 cm)												
TYPE	ONE WIRE SHIELDED				TWO WIRE SHIELDED				THREE WIRE SHIELDED		ONE WIRE DOUBLE SHIELDED	
CONFIGURATION												
WIRE SIZE	16	18	20	22	16	18	20	22	20	22	22	22
CONDUCTOR TO SHIELD pf/ft (30 cm)	89	91	74	98	65	65	64	63	60	52	98 (CONDUCTOR TO INNER SHIELD)	340 (INNER SHIELD TO OUTER SHIELD)
CONDUCTOR TO CONDUCTOR pf/ft (30 cm)					42	40	38	37	36	30		

Figure 3.4-8 Typical Capacitance of Various Types of Mil-Spec Shielded Wires

3.4.2 Interference Coupling at High Frequencies

High frequency signals may be defined as those for which the conducting wire lengths are longer than a quarter wave length of a given suspect frequency. For example, the wavelength of 30 MHz is 10 meters and a quarter wavelength is 2.5 meters. Thus, a conducting wire of 2.5 meters in length or longer may be susceptible to interference at 30 MHz. (See Section 3.4.2.2). For these wire lengths the distributed reactances cannot be considered as lumped values and standing waves may exist along their length. It is not useful to distinguish between magnetic and capacitive coupling since these lumped value concepts cannot be used because of standing wave and impedance variations. As a result, along its length a wire could be sensitive to magnetic or electric fields.

3.4.2.1 Coupling Effects

The emphasis at very high frequencies is on minimizing the circuit wiring dimensions of wire shield ground connections, by-pass capacitance ground leads and similar wiring associated with low impedance circuits. It is mandatory that the wiring of filters be carefully controlled to prevent inductive coupling between the input and output of the filter, which renders the filter ineffective.

At high frequencies, any open-ended wire should be given careful attention to determine if it is a pick-up point for high frequency excitation. Since small stray capacities will provide effective coupling to a high impedance point at high frequencies, wires can frequently be excited when they are attached to unused connector pins or open switch contacts. At a quarter wavelength distance, such open wires will be carrying maximum current and can readily couple into other wiring or circuits by the fields generated. An open wire may represent an effective antenna in the presence of stray electromagnetic fields. High radio frequencies are readily coupled into power wiring either magnetically or electrically, depending upon the standing wave which may be excited in the power wiring at the coupling point.

Conductive coupling is particularly difficult to avoid at high frequencies, since multiple point grounding may be required. A very short length of wire can represent an appreciable common inductive reactance to connected circuits. It is particularly important at high frequencies to insulate shielded cable sheaths so that they cannot make contact and form common return connections with other shielded cables. The wiring to a by-pass capacitor may represent more inductive reactance than the capacitive reactance of the capacitor, making it an ineffective by-pass and altering associated filter design constants.

3.4.2.2 Grounding Concepts at High Frequencies

At high frequencies, grounding concepts must be directed toward massive multiple grounding practices, since with single point grounding, standing waves may occur on ground leads. All connectors must be electromagnetically tight to reduce RF currents external to the shield. A massive ground plane should exist between equipments connected to the cable, and the cable should be carried close to the ground plane. A second alternative is the maintenance of no other ground path than the external cable shield between equipments; this is extremely difficult at very high frequencies because of paths to ground through stray capacity and power leads. The objective is to avoid RF currents to the external surface of the cable shield. Such currents can couple signals into or out of the inner cable wiring. To reduce such coupling, double shielding is frequently used in radio frequency cabling.

3.4.3 General Grounding Considerations

The aircraft ground system must meet the requirements for personal safety as related to the electrical power system, lightning protection of equipment and electromagnetic compatibility by providing a quiet, "earth" potential common/bus for the grounding of electronic equipment. The latter requirement is met by the

signal ground system as a part of the overall ground system. The signal ground system must function as a ground over a wide frequency range, as determined by the requirements of the instrumentation system.

Grounding techniques for the power systems and for lightning protection are well developed and have been well documented. Signal ground systems, however, still provide a problem area for the instrumentation engineer.

3.4.3.1 Power Grounds

There are two primary concepts regarding power ground returns. These are the structure common return and the wire common return. In the structure common return one side of the power system is grounded at the power source and all loads use the aircraft frame or structure as the return conductor. In three-phase connected ac systems the neutral is grounded at the source and all single phase loads use the structure for the return circuit. The principal advantage of this concept is the reduced weight resulting from the elimination of the many large gage power return wires. The disadvantage of this common return concept is that it does not distribute the power efficiently. The flow of currents throughout the structure produces voltage drops within the structure. Although these voltages are usually small as compared to the operating level of the power source, they are often of sufficient magnitude to create potential interference problems in any electronic system that chooses to use the aerospace vehicle structure as a power return. Even systems using the structure as a ground plane for shield ground are subject to induced voltages in susceptible circuits (see Section 3.4.4).

In the wired return concept all systems are grounded at one point only and use wires for all return circuits. The wired return system eliminates the vehicle structure as an impedance common to all systems and therefore greatly minimizes the problem of ground loops which exist with the common structure return concept. The reduction of ground loops and common impedance eliminates most of the instrumentation system interference problems.

3.4.3.2 Single or Multi-Point Grounding

Instrumentation installations very seldom have only one ground. In fact, in order to minimize instrumentation interference problems such as common mode coupling, (see Section 3.4.4.2) as many separate grounds as necessary are used. Ref. (B5). Separate ground planes for signal grounds, shield grounds, and primary/secondary power grounds are desirable. These individual ground planes are eventually connected by the shortest route back to the system ground point where they form an overall system ground reference. This method of grounding is usually called a single point ground.

The problem of using the single point ground method is in its implementation. For example:

- a. Equipments throughout the instrumentation system use interconnecting cables. These cables are often shielded.
- b. Parasitic capacitance exists between subsystems or equipments within a system because each chassis is carefully grounded to the structure on which it is mounted. The result tends to compromise the single point grounding attempt.

Cable shields and their grounds connect some of the subsystems together so that more than one grounding path from a given subsystem to the grounding point exists. At high frequencies, the parasitic capacitive reactance represents low-impedance paths and the bond inductance of an equipment-to-ground point results in higher impedances. The result is the possibility of common-mode current flow or unequal potentials developed among the equipments in all subsystems. Ref. (17).

The circumstances that tend to prohibit the implementation of a single-point ground technique support the idea of a multi-point ground. Thus, rather than trying to control shields, grounds, shield grounds and so forth, if all subsystems were heavily bonded to a common, low-impedance solid ground plane, common-mode currents and other EMI problems would be minimized. The problem here is that it is difficult to create a common low-impedance equipotential ground plane in an aircraft.

In reality the choice of which type of grounding method should be used can be resolved by pointing out that the single-point grounding method works better at low frequencies and a multi-point ground works better at high frequencies.

The decision to use single-point grounding or multi-point grounding requires a determination of where the low and high frequency changeover point is located for the subsystem involved. One method of determining this changeover point uses the decoupling-voltage transfer curve shown in Figure 3.4-9. At the low frequency end of the two curves shown the transfer curve shows a 6 dB/octave slope. Typical experimental data is plotted with the calculated approximation data. Two points are marked on the curve, one at $\lambda/16$ and one at $\lambda/4$.

Single point grounding is suggested for wire or cable lengths less than $\lambda/16$. Multi-point grounds are suggested for line lengths longer than about $\lambda/4$. The frequency range between the two points is a non-linear transition region as shown by the experimental data curve. Combinations of both single point and multi-point grounding may be required for line lengths in this frequency region.

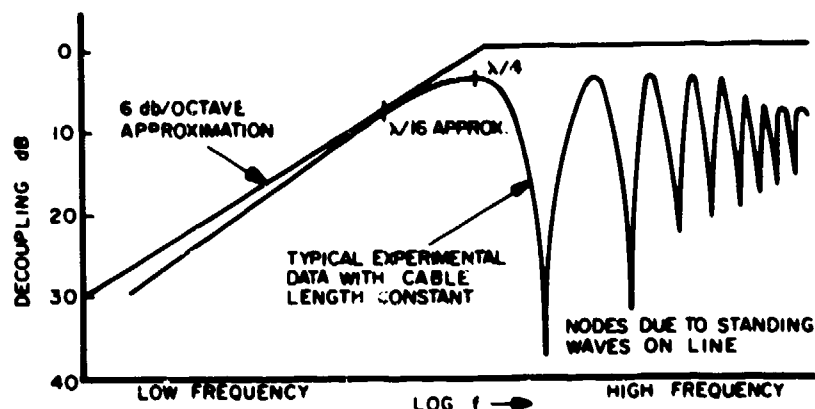


Figure 3.4-9 Decoupling-Voltage Transfer Characteristics for Both Calculated and Measured Data

The choice of the point $\lambda/16$ is somewhat subjective since the point arbitrarily identifies the end of the linear portion of the experimental data curve. There are some texts that select $\lambda/20$ as this point. Ref. (B5). (See Section 7.4.1.2).

3.4.4 Data Signal Grounds (Low Level)

All low level (1.0 volt or less) measurement systems must be provided with a stable ground plane. Its primary function is to assure that electronic equipment chassis are maintained at zero potential. A single point cannot have a voltage since the word "voltage" implies a potential difference between two points. Therefore, a system reference ground can be theoretically established by simply selecting a single point somewhere on the system ground plane. Ref. (B5).

Signals can be measured with respect to the system ground plane only if the system user can guarantee that all of the input signals will be fully floating with respect to the system ground plane. If the input signals are referenced to another ground, either accidentally or deliberately, then the difference in potential between the two grounds will either add or subtract from the true value of the signal being measured. To avoid this problem and to preserve flexibility, high accuracy low-level instrumentation systems should be installed using full-floating signal inputs.

When and if it is not practical to connect the signal source to the system ground, then it is necessary to establish a second low impedance grounding point. This second ground is generally called the signal ground. It is important that the signal ground also be a low-impedance path in order to reduce the voltage difference, the smaller this voltage difference, the smaller the common-mode voltage.

The signal ground is frequently isolated from other grounding planes and it is generally undesirable to connect the signal ground to the system ground unless it is done with a low impedance copper bus or its equivalent and then at one point only.

3.4.4.1 The Ground Loop

A ground loop is created by connecting together more than one type of ground plane to the same circuit. As pointed out earlier two separate grounds are seldom at the same absolute voltage. Therefore, their potential difference creates an unwanted current path in series with one of the signal leads as shown in Figure 3.4-10. Actually there are two ground loops shown in this figure.

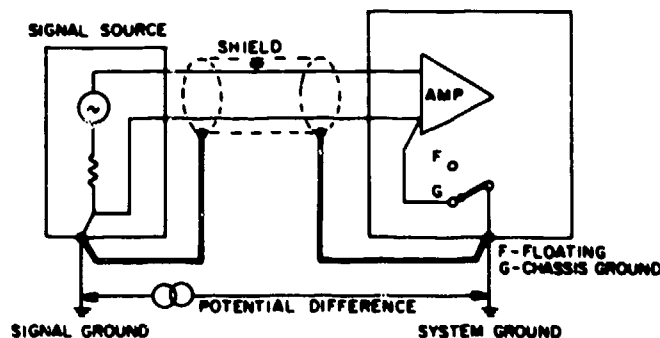


Figure 3.4-10 Improper Circuitry Showing Two Ground Loops

The first ground loop consists of the potential difference path existing between the signal ground and the system ground and in series with the lower amplifier lead wire. The second ground loop is shown by the heavy lines. The path is through the shield from the signal source to the amplifier. Alternating currents in the shield are coupled to the signal pair through the distributed capacity in the signal cable. This current then flows through the distributed capacity in the signal source impedance and to ground thus creating an additional noise signal. Either one of these ground loops is capable of generating a noise signal of sufficient magnitude to obscure the low-level data signal.

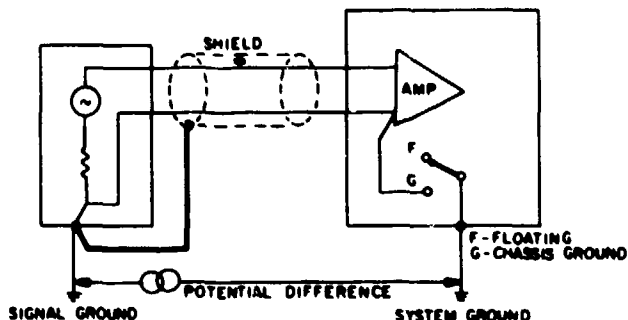


Figure 3.4-11 Elimination of Ground Loops Shown in Figure 3.4-10.

The circuit as shown in Figure 3.4-11 shows Figure 3.4-10 with the two ground loops eliminated. The signal lead wire ground loop is now open. The signal source and the signal cable shield are grounded only at the signal source and the ground loop through the signal cable shield has been eliminated by removing the shield to chassis ground jumper wire.

The following guidelines can be derived from the above discussion:

- A low-level data signal must have a stable system ground and a stable signal ground.
- Ground loops in either the signal circuit or the signal cable shield can affect the operation of a low-level data circuit.
- A signal circuit should be grounded at only one point.
- The signal cable shield should not be attached to more than one ground plane (or system).
- Ground the floating signal circuit and the signal cable shield only at the signal source.

3.4.4.2 In-Phase Signals & Common-Mode Voltages

A signal that appears simultaneously at both the amplifier input terminals with respect to a common reference point is referred to as an in-phase signal or by its more popular name, a common mode voltage. Since it does not contribute any useful data information to the system it must be classified as interference (noise) and rejected.

Common-mode voltages are not unusual or a special problem. But they are a constant source of aggravation that can occur in every low-level (less than one volt) instrumentation system in that the amplifier sees only a complex signal which is a combination of the data signal and the common-mode signal. To solve this problem, differential amplifiers with floating inputs are used. The differential amplifier rejects the common mode voltage and accepts only the data signal. The performance rating of such an amplifier ability to reject the common-mode voltage is called "common-mode rejection."

The common-mode voltages that create the most problems in low-level circuits are those generated by electromagnetic or electrostatic coupling in transducers and/or their signal wiring system.

3.4.4.2.1 Common Mode Rejection.

One of the most important procedures to follow in eliminating noise in low level systems is to assemble aircraft signal wiring so that any noise pickup will appear equally on both sides of the signal wiring pair, remain equal and appear simultaneously at both input terminals to the differential amplifier.

The following relationship shows how the wiring circuit conditions convert some of the common-mode voltage into an error voltage which is combined with the useful signal. (Reference Figure 3.4-12).

$$E_{nm} = E_s + E_{cm} \left(\frac{R_4}{R_1 + R_4} - \frac{R_3}{R_2 + R_3} \right) \quad \text{Eq. (3.4-4)}$$

where:

E_s = Signal voltage.

E_{cm} = common mode voltage.

R_1 = Signal source resistance to amplifier input terminal.

R_2 = Signal source resistance to amplifier input terminal.

R_3 = Leakage resistance to system ground from amplifier input terminal.

R_4 = Leakage resistance to system ground from amplifier input terminal.

E_{nm} = Normal mode voltage that is converted and appears across amplifier input terminals A and B.

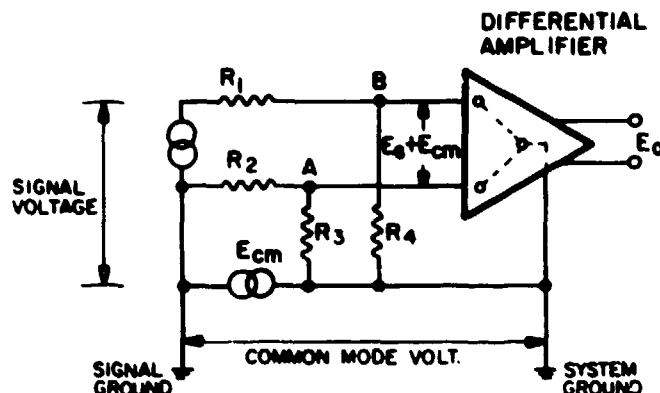


Figure 3.4-12 Common-mode rejection

As shown by Eq. (3.4-4) the common-mode voltage can be made zero if R_3 and R_4 could be made equal or infinitely large. Since these extremes are impractical to attain, it then becomes important to assemble a circuit that comes as close as possible. Accordingly, the following procedures are suggested:

- Select a signal source that has a low output impedance.
- Always use a "balanced line" from signal source to amplifier input. (see Section 3.4.1.2.1).
- Keep the signal wiring as short as possible. (see Section 3.4.1.1).
- Select a signal source which has a center tap on its output, if possible. (see Section 3.4.4.2.2).

3.4.4.2.2 The Amplifier Guard Shield

Differential dc amplifiers with floating inputs are generally designed with an internal floating shield which surrounds the entire input section. This floating internal shield is called a "guard shield" by most manufacturers.

The guard principle requires that the amplifier guard shield be driven by the common-mode voltage appearing at the two differential amplifier input terminals. This means that the guard shield must always be stabilized with respect to the incoming signal pair. Referring to Figure 3.4-13, this can be done as follows:

- a. Connect the amplifier guard shield to the signal cable shield and make certain that the cable shield is insulated from chassis ground or any part of the system ground. This assures that the internal amplifier guard shield is extended out along the entire length of the signal cable.
- b. Connect the center-tap of the signal source to the signal cable shield. If the signal source does not have a center-tap connect the signal cable shield to the low or shielded side of the signal source. This step stabilizes the amplifier guard shield and signal cable shield with respect to the signal source. (Note: the center-tap connection should not be used if the guard shield in the differential amplifier is permanently connected to one of its signal input terminals).
- c. Connect the signal cable shield and its tap at the signal source to the signal or transducer ground which should be located near to the signal source. Do not permit either the signal pair or the signal cable shield to contact any ground point. This procedure limits the maximum common-mode voltage to some value that is the difference in potential between the signal (or transducer) ground and the overall system ground.
- d. Ground the amplifier chassis, the equipment rack if one is used, the low side of the amplifier output and the output cable shield to the system ground. This final step stabilizes the data acquisition system with respect to the system ground.

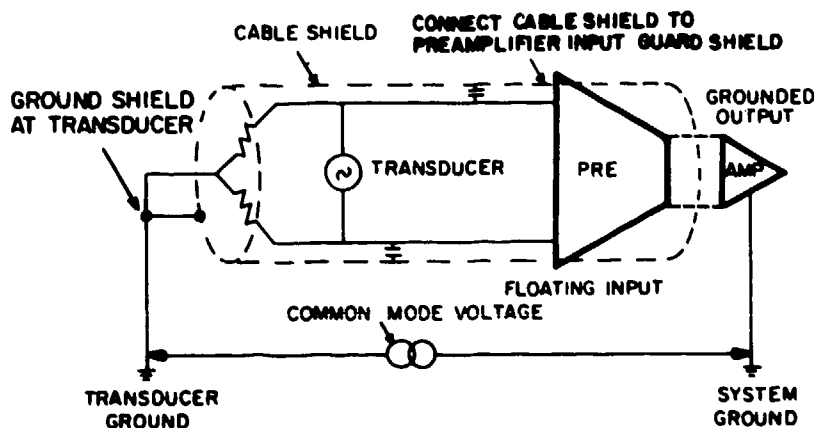


Figure 3.4-13 Preamplifier with "guard shield" input

3.4.5 Reducing Conductive EMI

One of the most effective methods of reducing the conductive EMI environment is through the proper harnessing and routing of wire bundles within the aircraft. (See Section 5.4.1). During the design and layout of the aircraft instrumentation installation each of the wires going to each of the sub-systems should be placed into bundles (harnesses) according to their classification. Wires that carry high power should not be put into the same bundle with those that carry data signals. Once the wires are put into bundles according to their function, they must again be classified according to their subsystem interfaces. This is done so that all of the wires serving one subsystem can have their shields returned on one wire and so each subsystem can have its own ground return.

Grounding systems are of particular importance because of their effect in minimizing EMI. It is also one of the most difficult to deal with. The reason for this is the fact that the various subsystems in the aircraft have been built by different people at widely separated locations. Each of the designers designs his subsystem about a ground plane within the subsystem. This creates the problem of segmented grounds which must be dealt with during the integration of the subsystems. It is very important, from the standpoint of EMI, that these different ground planes be made electrically the same as that of the aircraft. Any impedance in the connection of these ground planes to that of the aircraft is a possible point for the development of noise, particularly in the common mode component of the conductive EMI environment. A method of reducing this problem that is worth considering is the use of balanced systems. This entails the use of dc-to-dc converters, transformer coupling input and output signals in each of the subsystems. This allows the subsystem designers to design about his own ground plane, and for the subsystem to operate about this ground plane in the aircraft, since it could be kept isolated. The overall effect of this approach is to reduce the common mode and self-induced EMI.

Conductive isolation is generally accomplished through the use of transformer coupling. This provides a high impedance path to all spurious signals. The ratio of transfer for the spurious signals can be shown to be the same as the ratio of the interwinding capacitance to the capacitance across the transformer.

The use of conductive isolation has advantages and disadvantages. The advantages are that the use of conductive isolation greatly aids in the control of EMI, provides a balanced system and reduces the need for bulky and power consuming brute force filter techniques. The primary disadvantage is that it adds components to the subsystem and this can cause a reduction in the overall reliability of the equipment. These advantages and disadvantages must be weighed in determining whether or not to use the technique.

Too many engineers use elaborate schemes in order to control the reaction of their equipment to noise. Some of these schemes reduce the overall reliability of the equipment. Therefore, every effort should be made to use "simplicity" and good common sense.

If a proper amount of thought and research is put into the problem of EMI, the troubles that arise when a system is assembled will be greatly reduced. In the past these problems have been left to take care of themselves, the "cut and try" methods have been used at the time that the system was integrated. A little forethought and planning can eliminate the need for "fixes" at the last minute.

3.4.6 Bonding

Electrical bonding is the process of mechanically connecting certain metal parts together so that they will make a good low resistance electrical contact. Bonding is required to ensure that a system is electrically stable and relatively free from the hazards of lightning, static discharge, electrical discharge and to assist in the suppression of RF interference. In general, the resistance of an electrical bond should be in the order of 0.0025 ohm.

Grounding refers to the establishment of an electrically conductive path between a circuit and some reference point. The reference point can be earth, the equipment enclosure, or the aircraft structure. Good grounding techniques depend on good bonds. A uniform grounding philosophy is required to avoid conductive coupling, low-impedance ground loops and hazardous operations. Refs. (17, 18, 19)(B5).

3.4.7 Conduit Grounds

Conduit ground is generally used to prevent personnel shock hazards and to carry lightning current. Conduits, however, can also be a source of interference due to possible ground loops, conductive coupling, and/or poorly bonded connections.

Conduits made from solid or woven strands of metal may be used effectively to shield cables and wiring from RF radiation. However, to do so requires a good bonding to ground.

A good RF ground requires a short, high conductance lead. The inductive reactance of ground leads at radio frequencies requires a very short or leadless ground to avoid high impedance connections. Each length of conduit should be grounded at a single point. As the frequency increases even a relatively short bond to ground tends to become an effective radiator.

3.4.8 The Bond Strap

Many articles have been written on the subject of the bond strap and it is unnecessary to repeat available information. Ref. (20). However, from the point of view of installing an instrumentation system a few comments regarding their design may be helpful.

The best performing electrical bond is a permanent, direct, metal to metal contact such as that provided by welding or brazing, for example. Semi-permanent joints, such as provided by bolts or rivets can provide effective bonding. However, the relative motion of the joined members is likely to reduce the bonding effectiveness by introducing a varying impedance.

Bonding jumpers are relatively short, either braided or stranded conductors for application where interference, frequencies to be grounded are below 10 MHz.

To provide a low impedance path at RF frequencies, it is necessary to minimize both the self-inductance and the residual capacitance of a bond so as to maximize the parasitic resonant frequency. Since it is difficult to change the residual capacitance of the bonding jumper and mounting, self inductance becomes the main controllable variable. Thus, bond straps are preferable to round bonding jumpers of equivalent cross sectional area.

Solid metal straps are usually preferred for the majority of applications. Braided or stranded bond straps possess some undesirable features. Broken

strands may act as efficient antennas at high frequencies, and interference may be generated by intermittent contact between strands. Further, oxides may form on each strand of non-protected wire and cause corrosion. Because the corrosion is not uniform, the cross sectional area of each strand will vary. The non-uniform cross-sectional areas and possible resulting broken strands of wire may lead to generation of EMI within the jumper or strap.

A rather common use of the bonding strap is shown here in Figure 3.4-14. A bonding strap is required to electrically ground equipment that has been electrically isolated from the aircraft structure by shock mounts. This bonding is required to ensure that the equipment is electrically stable and relatively free from the hazards of electrical static discharge and to minimize RF interference.

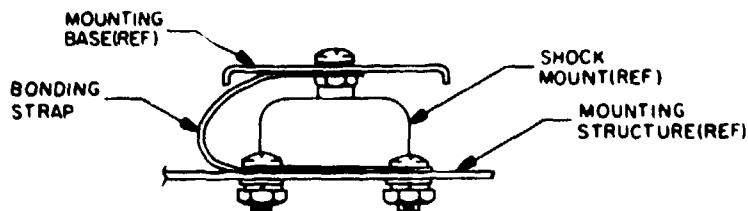


Figure 3.4-14 Shock Mount Using a Bonding Strap

The length of the bonding strap is its most important design criterion. The length is a major determinant in the bonding straps dc resistance. The length also determines the impedance at higher frequencies. Accordingly, both bonding jumpers and bonding straps should be no longer than 12.7 centimeters (5 inches) in length.

The width and thickness of the bonding strap are difficult to assess. But since the strap needs vertical and some horizontal flexibility it becomes apparent that the limiting factors are more mechanical than electrical. In general, a good mechanical design and proper installation will provide a satisfactory electrical design also. A useful guideline for achieving minimum bonding strap impedance (inductance) is to use a length-to-width ratio of approximately 5:1. Figure 3.4-15 shows the influence of bonding-straps and an AWG size 12 wire. Their impedance is compared as a function of frequency.

The metal used for the bonding strap should have low resistivity and be reasonably strong so that it will not fail during normal vibration and shock. Further, it must withstand whatever stresses may be imposed upon it during installation and equipment maintenance. Ref. (B3).

CURVE A- Solid Bond Strap
Length: 12.7 cm (5 inches)
Cross-section: 0.2 cm
(0.08 inch) diameter.
AWG size 12 wire

CURVE B- Braided Bond Strap
Length: 12.7 cm (5 inches)
Cross-section: 2.54 x 0.16 cm
(1 x 0.063 inch)

CURVE C- Solid Bond Strap
Length: 12.7 cm (5 inches)
Cross-section: 2.54 x 0.0076 cm
(1 x 0.003 inch)

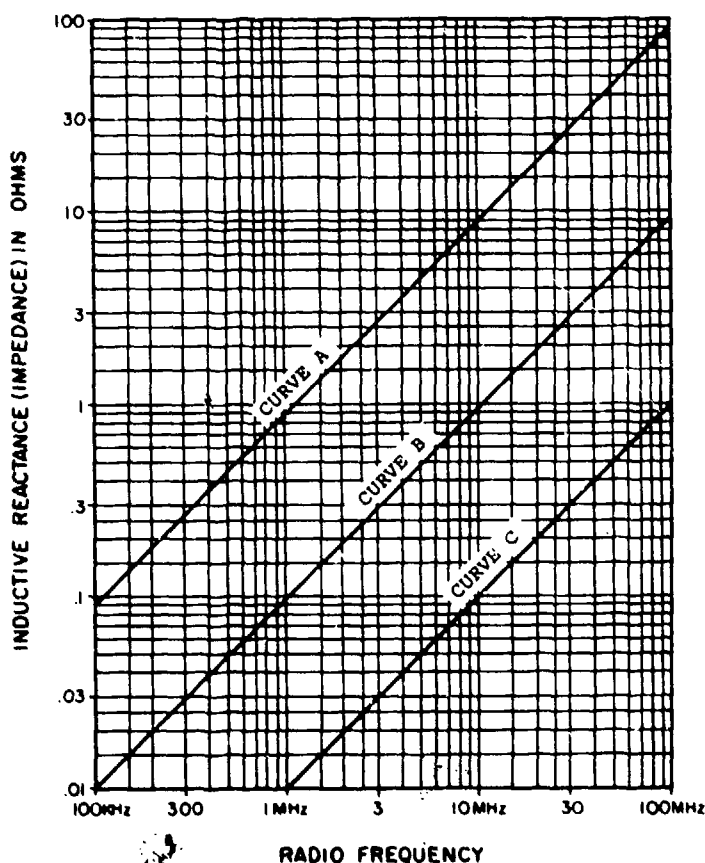


Figure 3.4-15 Impedance of Wire, Braided and Solid Bond Straps. Ref (B5)

3.5 Protective Isolation Systems

Sensitive instrumentation equipment is normally designed with integral mechanical isolation systems. However, in some circumstances isolation systems are not provided as part of the design. Accordingly, the instrumentation engineer should be familiar with some of the standard isolation methods.

In some cases the shock and vibration forces are so severe that it is not practical or even possible to design an equipment structure to withstand the environment. In such cases an isolation system must be used to bring the forces to within tolerable levels. Isolators are used for equipment isolation, dampers may be used to reduce peak amplitudes and special stabilizers are used when an unstable configuration of equipment is involved. Refs. (B2, B6, 21).

3.5.1 Shock and Vibration Damping

Damping is used to reduce shock and vibration amplitudes by dissipating some of the energy in the form of heat. Further, damping reduces resonant tendencies of structural members. There are four basic types of dampers:

1. Hysteresis
2. Viscous
3. Friction
4. Air

3.5.1.1 Hysteresis Damping

Hysteresis damping is the result of the gradual dissipation of energy that occurs within a flexing body due to imperfections in the elastic properties of materials. In a material that is not perfectly elastic, the strain energy is not recovered fully at each removal of stress. The energy lost is due to hysteresis and is dissipated in the form of heat.

3.5.1.2 Viscous Damping

Viscous damping results from the opposing force that a fluid generates to resist a change in motion. All fluids have an internal friction that resists relative motion between particles. The type of device that uses viscous absorption of shock and vibration is similar to that discussed for air damping in Section 3.5.1.4.

3.5.1.3 Friction Damping

Friction is the force which acts between the contacting surfaces of two objects and tends to resist their sliding motion. If the resistance to sliding prevents motion of one of the objects relative to the other, it is called static friction. If the resistance opposes the motion of both moving objects it is called kinetic friction. The force required to overcome static friction is shown here in the equation:

$$F_s = C_s F_c \quad \text{Eq. (3.5-1)}$$

where

- F_s = The force applied in the direction of motion, just sufficient to start the object moving.
- C_s = The coefficient of static friction is a constant for a given substance under given conditions.
- F_c = The force pressing the friction surfaces together.

A force, F_k , required to move an object with uniform velocity against friction is

defined by:

$$F_k = C_k F_c \quad \text{Eq. (3.5-2)}$$

where

- C_k = The coefficient of kinetic friction

If C_s is equal to C_k , the frictional force is defined as Coulomb friction. In general, friction materials do not provide a constant frictional force since the static friction does not equal the kinetic friction. Mathematically, however, in considering friction damping, it is assumed that the frictional force is constant, regardless of the position or velocity of the vibrating mass.

The Coulomb damping force is of a constant magnitude and is independent of displacement. Since the damping force is constant, this type of damping should not be used in a system that is excited at resonance unless the driving force is known to be less than the frictional forces.

3.5.1.4 Air Damping

Air damping results from the direct transfer of energy from a vibrating system to air. In comparison, air damping is a form of viscous damping. At room temperature, air has about one-fifteenth the viscosity of water and the damping obtained is very small compared to other forms of viscous damping. As a result, air dampers are preferred over friction or viscous dampers only for isolating light weight components.

A useful type of air damping system is the orificed dash pot. This type of air damping system does not rely on air viscosity alone. Since the damping system uses trapped air rather than free air, adiabatic and turbulence characteristics of air also become factors in its operation. The principle of operation is shown in Figure 3.5-1.

The damper is composed of a piston that fits tightly against the walls of a cylinder that has two holes at the top. Movement of the piston causes pressure changes within the chambers that force air out through the holes (orifices).

Air damping is incorporated into isolation mounts by means of a bellows that forces air through a hole as the bellow is distorted by the relative movement between the equipment and the mount. The force required to move the air through the hole is lost by the system and limits the amplitude and resonance.

A bellows sealed except for a hole is effective for motion in both the vertical and lateral directions. For example, the damper supported mass moves down, the bellows flattens and its volume is decreased. This increases the bellows internal pressure and air is forced out through the holes. As the damper supported mass moves up the reverse occurs and air is forced into the bellows through the holes. Lateral movement results in similar type of internal pressure differentials causing distortion of the bellows and thus effecting a damping action.

The column and wall thickness of the bellows are critical factors in the design of an air damper.

If the walls are too thin they will stretch during internal pressure build-up. The thicker the walls, the higher the shock-transmission factor.

It should be remembered that air damping generally has altitude limitations and cannot be used at high altitudes unless it is used within suitably pressurized compartments.

3.5.2 Isolators

Isolators used for airborne equipment may be categorized according to their construction and material used in the flexing or resilient element. The resilient element can be rubber, woven metal mesh, a coil spring or a combination of woven metal mesh and coil spring. The isolator performance is dependent upon the combinations used in the basic design.

3.5.2.1 Vibration Isolators

Vibration Isolators do not depend upon the dissipation of energy in performing their function of force or motion reduction. They operate on the principle of permitting the mounted equipment to move as it tends to move in response to the applied forces and to its inherent inertia. Isolators have relatively low stiffness to permit this motion of the equipment to take place without transmitting excessive forces to the support. This lack of constraint permits the mounted equipment to experience a relatively large motion if applied forces are large.

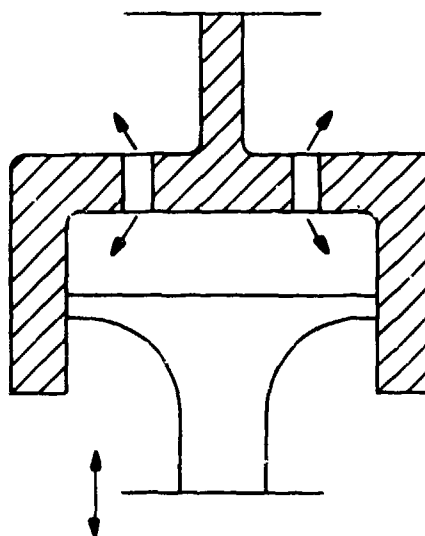


Figure 3.5-1 Principle of a Bellows Type Air Damping System

3.5.2.1.1 Rubber Isolators

Rubber has been used in isolators from the day that they were first designed, although cork is also used in ground systems, and until World War II all airborne applications used natural rubber. During the later parts of World War II and since then synthetics have been used instead of natural rubber and for most applications synthetic rubber possesses qualities that are far superior. For example, rubber synthetics maintain their elasticity and tensile strengths at higher temperatures better than natural rubber. In addition, the synthetics are less likely to deteriorate when exposed to oil.

The deflection of the rubber isolator tends to increase with time under conditions of continuous wear, particularly at elevated temperatures. This tendency to distort is known as drift or plastic flow. In an airborne environment this drifting can eventually result in a "bottoming-out" of the isolators during high amplitude vibration. For a properly selected rubber mount, the wearing should be conservative enough to compensate for drifting. Most manufacturers of isolation mounts include drift data as part of the descriptive literature.

There are two general types of construction for rubber isolators: open and cup types. The open type consists of a molded rubber form bonded to a metal mounting flange and a core. The core or cylinder is in the center of the isolator and attaches to the equipment. (See Figure 3.5-2).

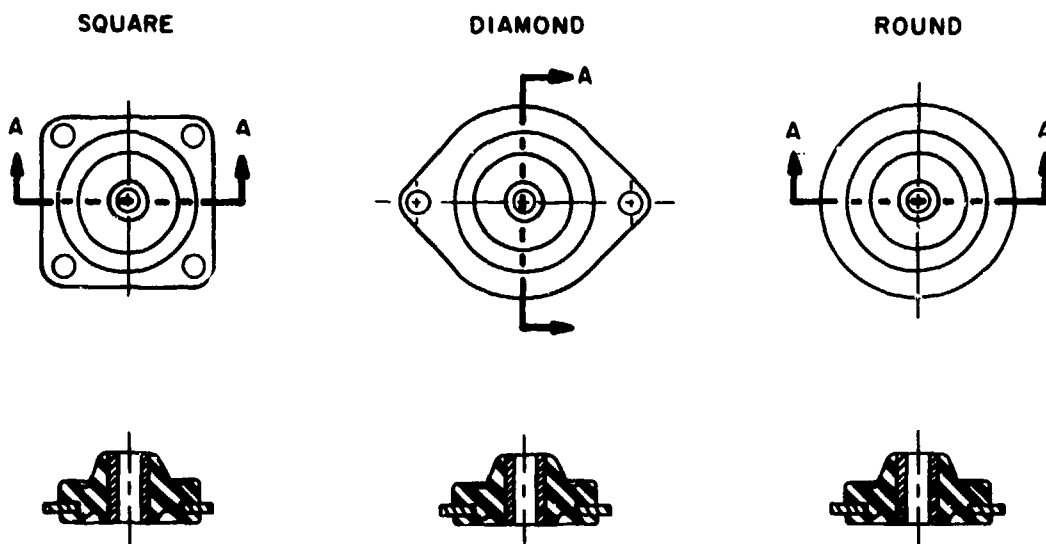


Figure 3.5-2. Examples of Rubber Isolators

The cup-type isolator has the rubber resilient element and its core enclosed in and bonded to the cup which acts as a housing. This design has the advantage over the open type in that if the resilient element fails, the cup and core will hold the equipment captive. The principle of operation is shown in Figure 3.5-3.

3.5.2.1.2 Metal Spring Isolators

The metal-spring type of isolator is shown in Figure 3.5-4.

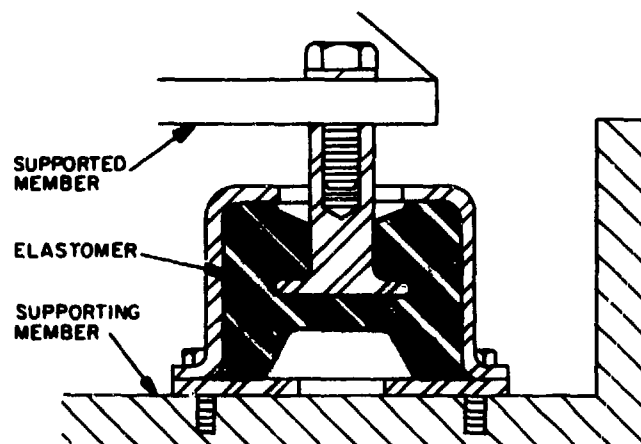


Figure 3.5-3 Cup-Type Isolator Principle of Action.

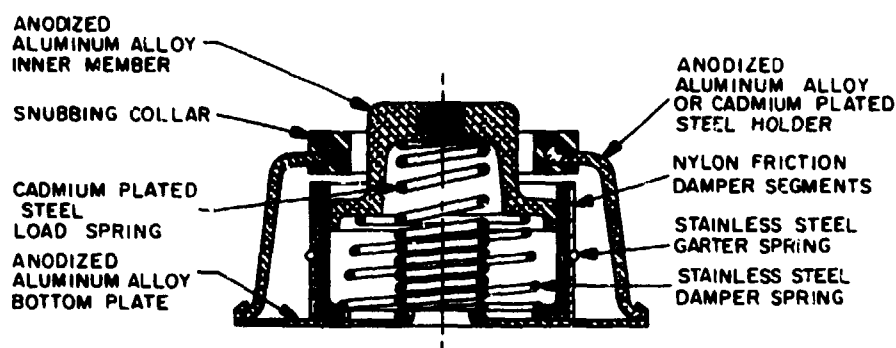


Figure 3.5-4. Metal-Spring Isolator, Cup-Type.

Metal springs do not drift, are least affected by temperature as encountered in aircraft equipments, and have a relatively long service life.

This type of isolator requires an auxiliary damping device, which may be a vented bellows, metal mesh or a friction damper as shown in Figure 3.5-4. The design uses a combination of damping devices, the nylon friction damper and a damper spring. (See Section 3.5.2.2).

3.5.2.2 Shock Isolators

Shock isolators have stiffer springs than vibration isolators and therefore have a higher natural frequency. The resilient elements of shock isolators are always non-linear, while it is not uncommon for a vibration isolator to use a linear spring. Some of the characteristics of shock and vibration isolators are compiled in Table 3.5-1.

Table 3.5-1 Comparison of Shock Vibration Isolator Characteristics.

SHOCK ISOLATORS	VIBRATION ISOLATORS
20-40 Hz natural frequency.	7-25 Hz natural frequency.
Resilient elements are very nonlinear.	Resilient elements are linear or nonlinear.
Natural frequency changes with amplitude vibration.	Natural frequency changes little or not at all with amplitude vibration.
Very little provision for equipment movement.	Provision for equipment movement.

Shock isolators are used for equipment mounts in environments where vibration is much less of a problem than is shock. For example, the shock isolator characteristics shown in Table 3.5-1 are not generally used for protecting equipment in manned aircraft. For environments experiencing high-amplitude low-frequency vibration, the use of shock isolators can be more detrimental to the equipment than rigid mounting. In conventional aircraft, severe shock is usually accommodated through the use of modified vibration isolators. Some of the methods used consist of a vibration isolator designed with stiffer linear springs or an added damper spring.

3.5.2.3 A Brief Comparison of Shock and Vibration Isolators

Vibration isolators are ineffective against shock, and shock isolators do not protect equipment from vibration frequencies below the $\sqrt{2}$ times the isolator's fundamental frequency. Therefore, the selection of the proper isolator depends on the frequency and magnitude of the mechanical excitation and quite often requires a compromise that will best satisfy the requirements.

Two idealized curves for the vibration amplitude of isolation mounted equipment are shown in Figures 3.5-5 and 3.5-6. Curve A shows the response of equipment on soft vibration isolators having a natural frequency of 8 Hz. Curve B shows equipment mounted on stiff shock isolators with a natural frequency 25 Hz. Isolator A, with a fundamental frequency of 8 Hz, begins to isolate at about 12 Hz. Isolator B, with a fundamental frequency of 25 Hz, does not offer any protection from vibration below 35 Hz. $(25)\sqrt{2} = 35$ Hz. Therefore, to protect against frequencies below 35 Hz the soft isolator of the type A is required.

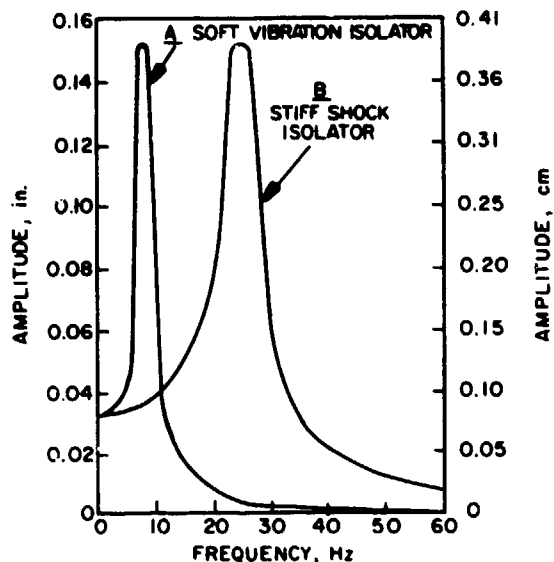


Figure 3.5-5 Response Curves for Two Types of Isolators. Ref (B2)

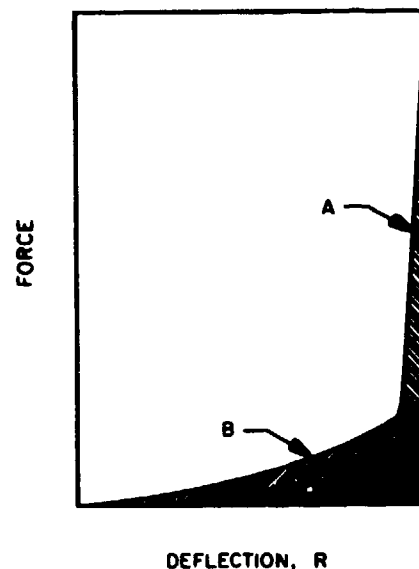


Figure 3.5-6 Force/Deflection Curves for Isolators in Figure 3.5-5 Ref (B2)

3.5.3 Stabilizers

While not strictly isolators, stabilizers perform an important function in the protective environment. During resonant or shock conditions, tall equipment, for example, that is bottom mounted can sway. A stabilizer can prevent this from happening. The stabilizer effectively has no stiffness in the vertical direction. Horizontal stiffness is provided by a resilient predesigned element that buckles under a light horizontal load. It buckles again under further increasing horizontal load and then stiffens slowly in compression under severe horizontal loads.

The stabilizer is placed between the equipment and rigid supporting structure as shown in Figure 3.5-7. Also shown (in the circled enlargements) are the characteristic movements during horizontal shock conditions.

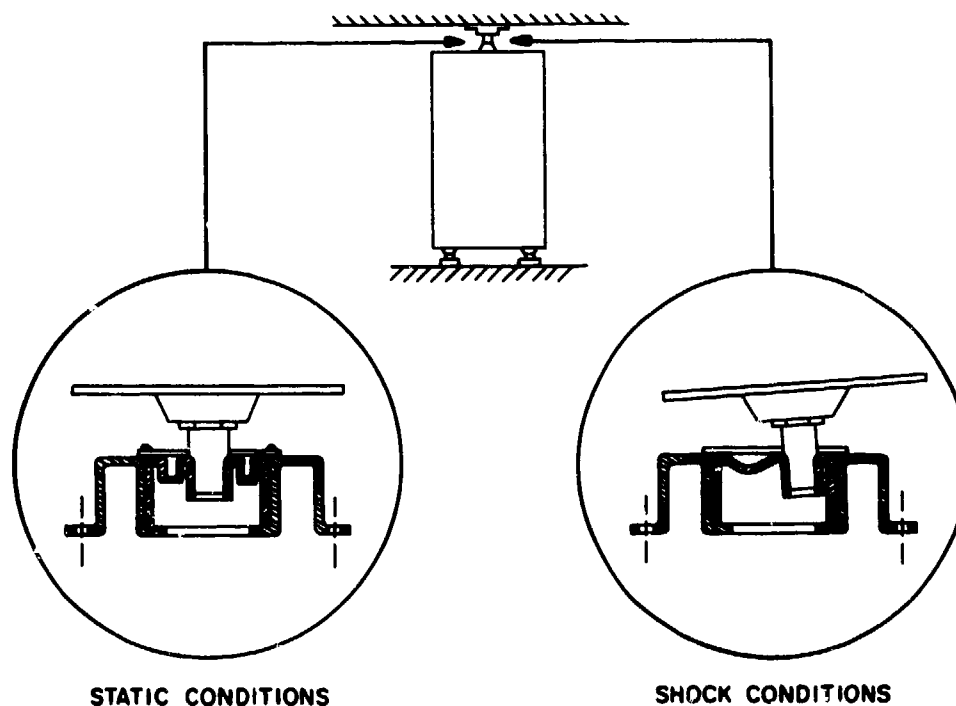


Figure 3.5-7 Stabilizer Under Static and Horizontal Shock Conditions. Ref (B2)

4.0 SELECTION OF INSTALLATION HARDWARE

The word hardware as used in this section refers to the wide variety of support items that are used to install, connect together, and protect both electrically and environmentally the major parts of the instrumentation installation. In order to illustrate some of the problems that may arise during hardware selection, several items common to all installations have been selected for discussion.

The hardware items discussed in this section were chosen on the basis that these items, perhaps more than any others, are not always given proper attention during the selection process.

4.1 Connector Selection Considerations

During the design of aircraft instrumentation systems, the selection of connectors is often set aside until other more apparent decisions have been made. Yet proper connector selection is as crucial to reliable instrumentation system design as are the active and passive components that make up the rest of the system.

Many engineers are indifferent to connectors. This attitude is encouraged by conflicting military specifications and the proliferation of poorly written vendor catalogs. Most of the system application problems result from the inability to determine the connectors' environmental capabilities since qualification tests are not written as they occur in real life. Consequently, laboratory testing often provides highly unrealistic results.

The interfacing of a connector with system components is a critical factor, for this is where the majority of operational problems occur, problems such as the type of connector contact, electrical performance, and connector mismatching. For example, an engineer may be very careful in selecting a connector with the proper environmental and electrical capabilities and yet completely overlook the design requirements for preventing connector mismatching. The instrumentation engineer must solve the problems that are left him by the connector manufacturer and the military specifications.

Prior to specifying the connector, a checklist should be made of all the installation and system operational factors. The checklist serves as a basis from which an adequate and reliable selection can be made.

4.1.1 Conflicting Military Specifications and Vendor Catalogs

In general, connectors are selected after a process of comparative evaluation, and the factors used in the evaluation reflect the user's needs and the applicable military specification (or other similar sets of fixed requirements). However, user experience is probably the best source of information about connector performance. Just how important user experience is can be illustrated by comparing published vendor data with vendor-quoted military specifications, as described below.

Temperature range is a significant indicator of connector performance, and for this reason is often used as a selection criterion. Figure 4.1-1 is taken from a vendor brochure describing the performance of a low profile connector designed to military specification MIL-C-38999. Note that there is no change letter following the military specification number. This indicates that the vendor design relates to the basic military specification, which was released in October of 1966. Figure 4.1-2 presents the applicable paragraphs of the quoted military specification as they were written in October 1966.

The operating temperature range of the connector described in Figure 4.1-1 is "-29° C to +200° C (-85° F to +392° F)". However, -29° C does not equal -85° F. There is no way to know which temperature is correct without calling the vendor. There is a similar discrepancy in the military specification. In Figure 4.1-2 (a), the maximum operating temperature for series IIB connectors is 200° C (392° F), as quoted by the vendor. Ref. (22). The discrepancy occurs in Section 3.6.1 of the subject MIL Specification where the environmental temperature requirements are stated to be 177° C (392° F). Refer to Figure 4.1-2(b).

**SCOOP-PROOF AND LOW PROFILE CONNECTORS...
DESIGNED TO MIL-C-38999**

- High contact density
- Lightweight/low-profile/scoop proof
- Environment-resistant
- Operating temperature range from -29°C to +200°C (-85°F to +392°F)
- Crimp snap-in contacts in the rear release contact retention assembly

miniature circular connectors are environment-resistant and designed to meet the critical performance and design requirements of MIL-C-38999. Engineered for high density circuit capabilities, these connectors are designed to operate at temperatures ranging from -29°C to +200°C (-85°F to +392°F). They are readily adaptable to both commercial and space age requirements where size, weight, low-profile/scoop proof design and high reliability are key factors. connectors are offered in nine shell sizes. A total of 59 contact arrangements are available that will accommodate from 3 to 128 contacts using AWG wire sizes 16 through 28. Contacts are of high conductivity copper alloy with gold plated finish.

Figure 4.1-1 Vendor Data Quoting Military Specification Performance and Design Criteria

1.3 Classification. Connectors. Connectors fabricated to this specification are classified as follows:

a. Series:

- I - LJT Grounded - 150°C (302°F) Max. operating temp.
- II - A. JT Low Silhouette - 150°C (302°F) Max. operating temp.
- II - B. JTS Low Silhouette - 200°C (392°F) Max. operating temp.

(a) Connector Classification.

3.6.1 Environmental Requirements. Connectors shall be capable of satisfactory performance, during or after, as applicable, subjection to the following environmental conditions:

a. Temperatures from -55°C (-67°F) to 150°C (302°F) for Series I and IIA connectors. Temperatures from -55°C (-67°F) to 177°C (353°F) for Series IIB connectors with the exception of solder-mount receptacles which have an upper limit of 150°C.

(b) Connector Temperature Requirements.

Figure 4.1-2 MIL-C-38999, October 1966.

Figure 4.1-3 shows the current version of the military specification, MIL-C-38999 (G), which was released in December 1977. In this version, the design operating temperature range is stated to be -65°C (-85°F) to 200°C (392°F), indicating that the lower temperature limit compounds the confusion caused by the discrepancy in the vendor advertisement, because it looks as if the connectors have been designed to meet the later military specification and not the one quoted.

This example demonstrates that the instrumentation engineer is at a disadvantage if he must rely entirely on brochures, catalogs, or even military specifications for meaningful connector performance criteria.

The instrumentation engineer, in addition to having to deal with inconsistencies in the stated performance criteria, must decide whether the equipment will perform as stated in the environment of his particular application. In the past, environmental specifications have always been especially difficult to interpret for airborne system applications. The following questions illustrate the types of factors that must be considered:

1.2.1 Design considerations. Connectors are capable of satisfactory performance during or after, as applicable, subjection to the following environmental conditions:

1.2.1.1 Temperature. Temperatures from -65° (-85°F) to +200°C (392°F) (see 1.3.1d).

(a) Connector Classification

d. Temperature ranges:

Series I and II: Finishes -

- A - Bright cadmium plate over nickel (conductive) -65° to +150°C (inactive for new design).
- B - Olive-drab cadmium plate over a suitable underplate (conductive) -65° to +175°C.
- C - Anodic (nonconductive) -65° to +200°C.
- D - Fused tin, carbon steel (conductive) -65° to +150°C.
- E - Corrosion resistant steel passivated (conductive) -65° to +200°C.
- F - Electroless nickel coating (conductive) -65° to +200°C.
- N - Hermetic seal or environment resisting corrosion resistant steel (conductive plating) -65° to +200°C.

Series III and IV: Classes -

- C - Anodic (nonconductive) -65° to +200°C.
- F - Electroless nickel coating (conductive) -65° to +200°C.
- K - Corrosion resistant steel passivated (conductive) -65° to +200°C.
- W - Olive-drab cadmium plate over a suitable underplate (conductive) -65° to +175°C.
- Y - Corrosion resistant steel passivated (conductive) -65° to +200°C.
- N - Corrosion resistant steel with electrodeposited nickel plating (conductive) -65° to +200°C.

(b) Connector Temperature Requirements

Figure 4.1-3 MIL-C-38999G, December 1977.

Are the vendors' tests made using specified load current or de-rated current? This is important, because quite often the connector is not evaluated using all the connector pins.

Do the evaluation tests include all of the connector parts assembled as a complete connector? Usually the test procedure is not explicit. Specifications for testing often say merely that a "wired, mated connector shall be subjected..."

Are the listed specifications meaningful? The data may not be relevant for the intended application. Many specifications state clearly that the test conditions are seldom directly related to actual environmental conditions.

Thus, before an engineer can decide which connector is proper, he must read all related material completely and carefully.

4.1.2 Connector Environmental Considerations

The requirements of high performance aviation and missile instrumentation have generated more realistic connector specifications. These specifications reflect the need for connectors to withstand the combined effects of wide variations in temperature, shock and vibration, and atmospheric pressure and environmental moisture. Further, some connectors may have to withstand corrosion, explosion, or physical abuse.

4.1.2.1 Temperature

As shown in Figure 4.1-4, with forced convection, the connectors available today not only operate continuously at 200°C (392°F) but can also maintain an environmental seal against air and moisture despite thermal expansion and compression or thermal shock.

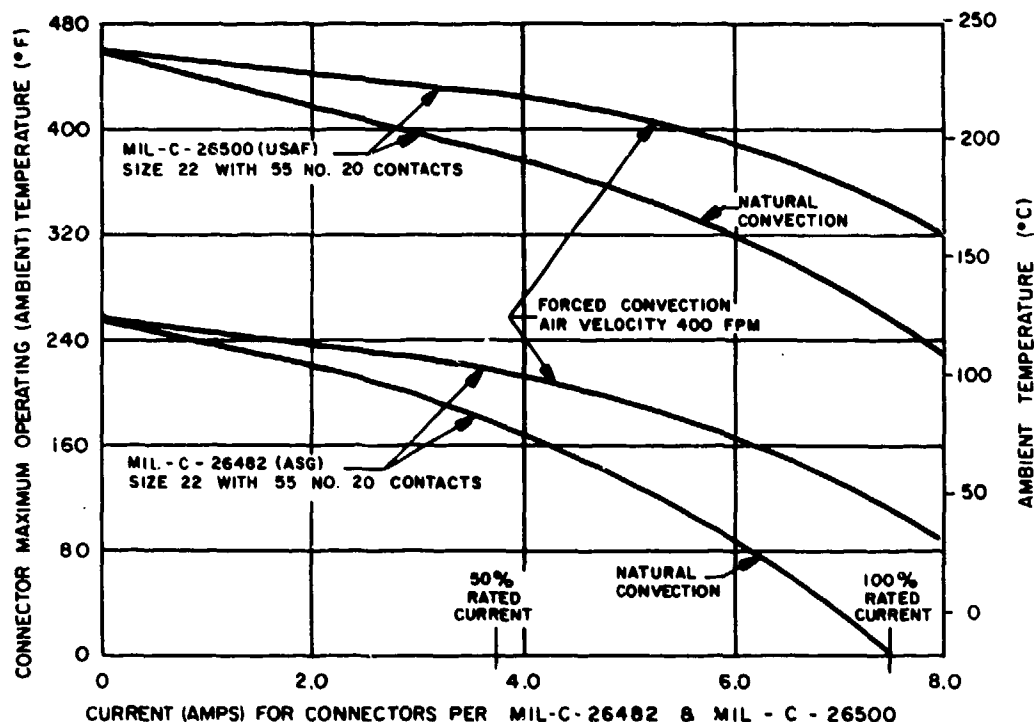


Figure 4.1-4 Maximum Ambient Temperature versus Typical Sustained Current Capability MIL-C-26482 and MIL-C-26500 Connectors.

For many years airborne (MIL-C-5015 and MIL-C-26482 type) connectors were considered to be capable of operating in 125°C (257°F) ambient temperatures. This interpretation was based upon thermal shock (i.e., temperatures cycling from -55°C (-67°F) to 125°C (257°F)) rather than upon any consideration of the continuous current-carrying capabilities at 125°C (257°F).

The need to provide connectors capable of continuous operation at high temperatures required a careful study of the combined effects of temperature and current as a function of time. As shown in Figure 4.1-4, the MIL-C-26482 connector would have to operate in ambient temperatures well below 125°C (257°F) when carrying any appreciable current.

Also shown in Figure 4.1-4 is the MIL-C-26500 type connector. The two curves indicate a considerable improvement at 200°C (392°F) while carrying 50% rated current. Notice also that the connector can operate continuously at 125°C (257°F) at 100% rated current.

Figure 4.1-4 illustrates the sustained current capability of the connector as a function of ambient temperature. The figure does not reflect connector contact temperature, which is the sum of ambient temperature and the temperature rise due to the flow of electrical current through the connector; this is shown in Figure 4.1-5 for a MIL-C-26500 series connector.

Figure 4.1-5 graphically illustrates the exposure time limitations of two different connector sizes based on a contact temperature of 239°C (462°F). The ampere ratings are taken from MIL-W-5088 G for a wire gage of 20. For example, a 12-pin connector can operate continuously at 120°C (250°F) with an individual contact current of 7.50 amperes. However, the same contacts carrying 3.75 amperes can operate continuously at nearly 205°C (400°F). The limiting factor is the contact temperature of 239°C (462°F). Figure 4.1-6 identifies the contact wiring geometry for the connectors used in Figure 4.1-5. Ref. (23, 24).

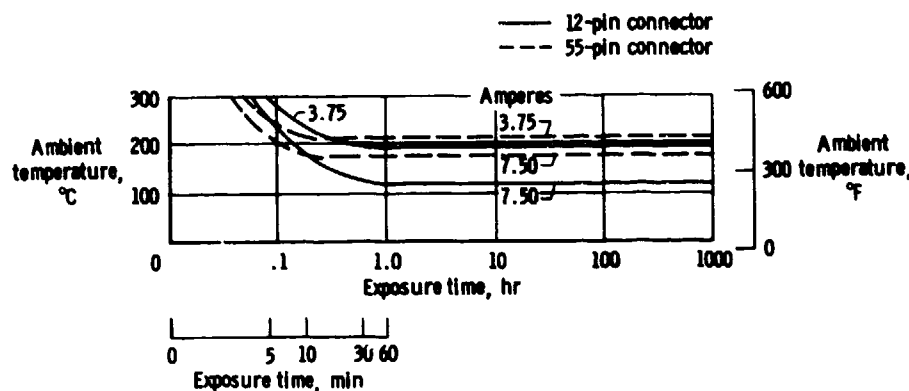


Figure 4.1-5 Connector exposure time and temperature limitations based on contact temperature of 239°C (462°F). Based on MIL-C-26500.

One of the most common errors in selecting a connector is to disregard the similarity of a wire bundle and a connector. The instrumentation engineer must remember that a single AN 20 gage wire in free air can safely carry 11 amperes. This same size wire in a bundle or conduit can carry only 7.5 amperes, however. The use of multi-pin connectors like those shown in Figure 4.1-6 should be considered as a wire bundle and derated, if required, for current capacity.

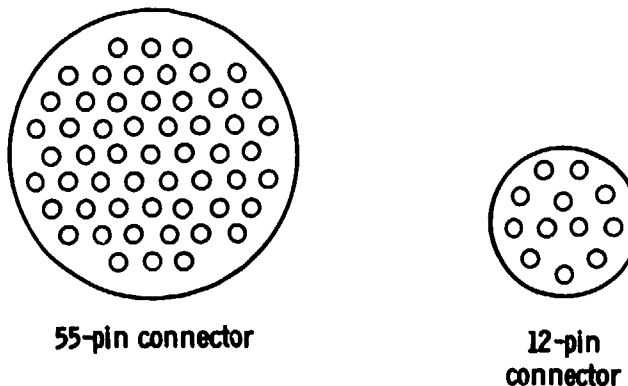


Figure 4.1-6 Connector Wiring Geometry Evaluated in Figure 4.1-5.

Connector performance is affected not only by temperatures that are elevated for long periods of time, but also by wide and rapid variations in temperature, or thermal shock which can cause elastomers, plastics, and metals to expand or contract at different rates. This may cause seals and insulation to fail, making the connector more vulnerable to moisture and corrosion.

4.1.2.2 Shock and Vibration

Among the most severe mechanical stresses to which a connector can be subjected are those induced by vibration. In general, connectors cannot be protected by external shock-absorption techniques. Instead, they must be self-damping to prevent contact chatter.

The selection criteria for connectors that are required to withstand high levels of vibration and shock are basically mechanical: the smaller their size and weight the better. Careful consideration should be given to vibration before overly large connectors are selected. Furthermore, the connector specifications should be checked to be certain that the vibration specifications are meaningful. The vendor's test conditions often do not represent the environment in which the

connector is to be used. A typical example are tests performed using only one environment at a time. Vibration testing should be done during temperature cycling, etc.

4.1.2.3 Pressure and Moisture

Trapped air and moisture can both contribute to voltage breakdown in a connector, particularly if pressure changes like those that accompany changes in aircraft altitude are involved. In aircraft applications, another environmental factor must also be considered: Aircraft may fly only on sunny days, but the use of toxic fuels may require that the aircraft be thoroughly washed with water after landing.

A connector may be designed to be resistant to moisture, but improper installation may destroy or degrade this resistance. Thus, careful consideration of connector specifications and careful review of connector installation procedures are necessary for satisfactory connector performance.

If operation in a low pressure/high altitude environment is anticipated, the connector insert should be chosen accordingly. Properly designed inserts provide an effective high altitude corona barrier as well as protection against low altitude voltage breakdown.

4.1.2.4 Corrosion

In most aircraft, the bulk of the instrumentation system is located within a confined instrumentation bay. However, some sensors and their connectors may be subject to corrosive fumes or fuels, and these must be carefully selected. In addition, in some aircraft the fumes from corrosive fuels may penetrate the instrument bay. The connectors in all such areas must be carefully inspected immediately before every flight. Intermittent circuit operation often indicates that the connector pins are contaminated; under these circumstances the contacts must be carefully cleaned. Therefore, the instrumentation engineer must review the connector environment carefully and select the connectors that are appropriate for these installations.

4.1.2.5 Explosion

The hazard in operating any electrical connector in an explosive atmosphere is possible sparking. The sparking that occurs while mating or demating a connector can be isolated by using an explosion-proof connector that mechanically isolates the contacts prior to mating or demating. This can be done by using a

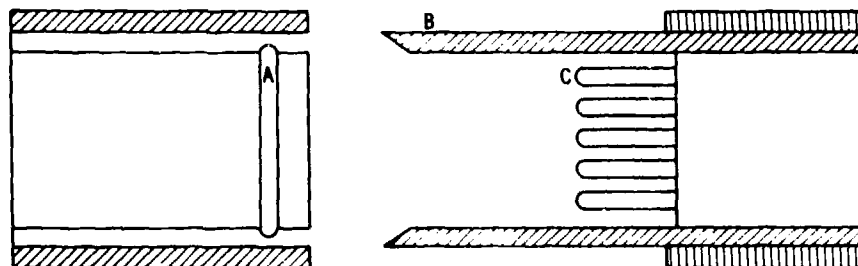


Figure 4.1-7 Basic Explosion-Proof Connector Design

shell and insert design of the type shown in Figure 4.1-7. In Figure 4.1-7, A is a compressible seal that forms with B as the connector shell is inserted. The pins, C, do not mate until this seal is well established.

4.1.2.6 Physical Abuse

Overly large connectors are often used as bulkhead connectors, and the proper tool for their mating and demating is a web-wrench. Large pliers or jaw type tools with teeth should never be used to mate or demate these connectors.

No doubt other environmental hazards exist that have not been mentioned. However, the instrumentation engineer should follow the same procedure in each case: he should find out the requirements of the environment and select the connector accordingly.

4.1.3 Selection of Connectors

Among the considerations that affect the choice of connectors are the appropriate connector and contact size and the appropriate connector type in terms of connector configuration and contact material. In addition, the connector choice should reflect not only present needs but also allow for future system growth.

4.1.3.1 Contact Size (Wire Gage)

Signal and power wiring are routed through separate connectors, a practice which results in additional connector requirements. For example, wire gage must usually be no smaller than AN 22 or, in some cases, AN 24 due to the minimal tensile strength of the wire. This limitation may constrain the choice of connector and contact density.

4.1.3.2 Contact Materials

To permit an electrical connector to be repeatedly mated and demated, pin and socket contacts are used. These contacts represent one of the most important parts of the electrical interconnection system. It is the responsibility of the instrumentation engineer to design an adequate and reliable interconnection system, because without good contacts, the interconnection system is useless.

Copper alloys are the most commonly used base materials for electrical contacts. During the 1940's most contacts were silver plated. When requirements such as prolonged storage became more common, the silver plating was thinly coated with gold to prevent tarnishing and corrosion. However, the silver migrated through the gold, corrosion occurred, and the resulting increase in contact resistance was wrongly blamed on the gold coating. Ref. (25).

The time it takes for migration to occur can be extended by using a gold plating of 762×10^{-6} to 1270×10^{-6} millimeter (0.00003 to 0.00005 inch). Further, if several successive platings of gold are used, the contacts can be used at ambient temperatures up to 200°C (392°F). Above this temperature, more expensive materials such as rhodium must be used for plating. Unfortunately, however, rhodium is not as good a conductor as gold.

Another difficulty with gold plating is encountered during soldering. When gold plating on a contact is heated, an alloy forms with the solder. This alloy has a high melting point, often creating a cold solder joint. Fortunately, this problem can be avoided by using crimped contacts.

The use of gold and other precious metals for electrical contacts is being re-evaluated for another reason: the high price of the metals themselves. One way to reduce costs is to use less metal. For many years some specifications

have quoted a gold plating thickness of 2540×10^{-6} millimeter (0.0001 inch). However, this thickness specification has been reduced by half, as evidenced by MIL-G-45204B. In fact, most non-military ground applications now use a gold

plating thickness of 508×10^{-6} to 762×10^{-6} millimeter (0.00002 to 0.00003 inch).

Another way to reduce cost is to use leaded nickel/copper as a base material for contacts in place of brass, beryllium/copper and phosphor bronze. Leaded nickel/copper is easy to machine, resists oxidation, solders readily, and, according to the vendor's brochure, has low contact resistance.

4.1.3.3 Contact Resistance

Whenever there is an interconnection in an instrumentation wiring system, the resistance due to the contact becomes part of the circuit. However, contact resistance makes up only part of the total resistance in a circuit, which consists of source, line, contact, and load impedances. However, total resistance is often difficult to determine. Vendors often neglect to state the contact size, maximum current, test current, and potential drop, and refer the user to the appropriate military specifications, which in turn often give information that is irrelevant for the purpose.

Past experience has shown that contact resistance must be determined analytically. Any attempt to actually measure contact resistance in an existing electrical circuit in an aircraft will be less than satisfactory, because in order to measure the contact resistance, the connectors somewhere within the interconnecting wire must be disconnected. Consequently, the resistance due to the disconnected connectors cannot be measured. Furthermore, it cannot be assumed that the resistance of a contact or circuit is the same before and after the circuit has been broken. The resistance of a given contact no doubt changes each time the connector is re-mated. Finally, the airborne environment may cause special problems not readily measurable on the ground.

Contact resistance is not readily determined, but in general, this is not a problem, not because contact resistance should be ignored but rather because actual resistance problems are more likely to be related to inadequate contact seating, a defective crimp or solder joint, or a poor connector mating. Ref. (26).

To give an idea of the magnitude of contact resistance as compared with total circuit resistance, total circuit resistance can be expressed as follows:

$$R_t = R_{\text{wire}} + R_{\text{contact}} + R_{\text{source}} + R_{\text{load}} \quad \text{Eq. (4.1-1)}$$

where R represents resistance and R_t is total circuit resistance. Then the following values may be assigned for a typical example: $R_{\text{wire}} = 2$ ohms, $R_{\text{source}} = 5$ ohms, and $R_{\text{load}} = 120$ ohms. For illustration purposes, perform the calculation using each of three values for contact resistance:

$$R_{\text{contact}_1} = 10 \times 10^{-3} \text{ ohms}, R_{\text{contact}_2} = 20 \times 10^{-3} \text{ ohms}, \text{ and } R_{\text{contact}_3} = 30 \times 10^{-3} \text{ ohms}$$

The equations for these three values of contact resistances are then as follows:

$$R_t = 2 \text{ ohms} + 10 \times 10^{-3} \text{ ohms} + 5 \text{ ohms} + 120 \text{ ohms}$$

$$R_t = 2 \text{ ohms} + 20 \times 10^{-3} \text{ ohms} + 5 \text{ ohms} + 120 \text{ ohms}$$

and

$$R_t = 2 \text{ ohms} + 30 \times 10^{-3} \text{ ohms} + 5 \text{ ohms} + 120 \text{ ohms}$$

or

$$R_t = 127 \text{ ohms} + 10 \times 10^{-3} \text{ ohms}$$

$$R_t = 127 \text{ ohms} + 20 \times 10^{-3} \text{ ohms}$$

and

$$R_t = 127 \text{ ohms} + 30 \times 10^{-3} \text{ ohms}$$

Clearly, contact resistance is very small compared to total circuit resistance.

The same point can be illustrated in another way. The percentage of change due to contact resistance may be expressed as $\frac{R_{\text{contact}} \times 100}{R_t}$.

Therefore, for R_{contact_1} the effect of contact resistance is $\frac{10 \times 10^{-3}}{127}$

$\times 100 = 0.0079$ percent. For R_{contact_2} it is $\frac{20 \times 10^{-3}}{127} \times 100 = 0.0157$

percent, and for R_{contact_3} it is $\frac{30 \times 10^{-3}}{127} \times 100 = 0.024$ percent.

In the example above, a circuit with only one contact was evaluated, and it was assumed that the connector was properly assembled and mated. In practice, several contacts may exist in a single circuit. For extremely low voltage applications, however, such as in low millivolt sensor circuits, contact resistance makes up a higher percentage of total resistance. In these applications, the number of connector contacts should be minimized, particularly if the input impedance of the sensor amplifier is less than or equal to $10(R_{\text{contact}})$.

Contact temperature is the total of ambient temperature and the temperature rise due to the flow of electrical current through the connector. The effect of contact temperature on contact resistance can be calculated by using the formula

$$R_t = R_0 [1 + \alpha(t - t_0)] \quad \text{Eq. (4.1-2)}$$

where

R_t = resistance of a conductor at the temperature t , ohms

R_0 = resistance of the conductor at the temperature t_0 , ohms

α = temperature coefficient of resistivity, that is, the ratio of the change in resistivity due to a change in temperature. The dimensions of this quantity may be expressed in ohms/ $^{\circ}\text{C}/\text{ohm}$ or ohms/ $^{\circ}\text{F}/\text{ohm}$.

For example, the temperature coefficient of resistivity, α , for annealed copper is 0.00393. For a one percent increase in operating temperature, the resistance will increase by nearly 0.4 percent.

4.1.3.4 Contact Types

Conductors are usually attached to the connector pins and sockets (or contacts) in one of four ways: soldering, crimping, welding, or wire wrapping. Each has advantages and disadvantages in terms of quality, ease of performing the connection, and speed of repair in the shop or field. Ref. (26).

4.1.3.4.1 Soldering

When properly done, a soldered connection is a nearly perfect joining for two conductors. Yet soldering does have disadvantages. Some of them are:

- A tendency to corrode. (Even resin core corrodes in the presence of moisture.)
- The amount of training and certification required.
- The absolute necessity of cleaning the joint.
- The need for close temperature control.
- The fact that soldered joints are only good at temperatures up to 149°C (300°F).
- The wide variety of hand tools required.

4.1.3.4.2 Crimping

Crimping has become the most popular joining method for multicontact connectors. Its advantages are:

- It is noncorrosive.
- Skill requirements can be minimal if one type or size of crimp contact is called for. (Experience is necessary to recognize the differences between various types and sizes of crimp contacts; accordingly, this could be a disadvantage.)
- A joint can be adequately inspected visually (through the inspection hole in the body of the contact.)
- Cleaning the joint materials is not necessary.
- Field rework is easy, since few special tools are required.
- Because of the crimping tool's characteristics, the quality of crimping is uniform.
- Crimped connections are light in weight.
- Crimping is fast and simple.

The disadvantages of crimping are as follows:

- The crimping tool requires an insert for each different contact gage.
- Periodic calibration is required for the crimping tool.
- Crimping tools are initially expensive.
- A variety of tools and inserts must be available to handle the variety of manufactured contact types.

4.1.3.4.3 Welding

Precision welding machines have increased the acceptability of this method for joining conductors and contacts. The advantages are:

- Welding can be automated, which provides fast, reliable joints and eliminates many human factors.
- The joints can withstand high temperatures.
- The joints are strong mechanically, usually stronger than the wire itself.

The disadvantages of the system are:

- Visual inspection is not practical.
- Welding equipment is expensive.
- Cleanliness and surface preparation are absolutely essential.

- Specialized training is necessary.
- Field rework is not practical.

4.1.3.4.4 Wire Wrapping

The wire wrapping operation depends more on the tool than on the operator for high quality results. Despite the advantages of the technique, however, wire wrapping has not generally been accepted in the flight testing environment. The wire wrapping operation has been accepted, however, as a reliable attachment technique internal to electronic chassis where the wrapped contact will never be disturbed. The advantages are:

- The hand tools are inexpensive.
- The procedure is fast and easy to learn.
- The wrapping procedure is nonchemical and nonheating.
- Preliminary preparation of the wire wrap terminal and wire is not required.
- Joints are field repairable.

The disadvantages are:

- The technique generally requires the use of solid rather than stranded wire.
- Stranded wire, if used, must be presoldered.
- Contact density is limited, particularly in miniature connectors.
- Re-use of posts is limited.
- A wide variety of wrapping bits is necessary.

4.1.3.5 Connector Contact Requirements

During system installation design the instrumentation engineer must take system expansion into consideration. Spare contacts must be available in each connector. Thus, the requirement for spare contacts will affect the choice of connector size and the quantity of connectors purchased. Typically, the number of spare contacts required is 10 to 15 percent of the individual connector density. The overall instrumentation connector and contact requirements should be continuously reviewed to insure the availability of spares.

To permit future system growth or possible contact failure there should be spare connector contacts for all of the wiring sizes used in the instrumentation system and for all of the special purpose contact types, such as those used for thermocouples. Further, during system instrumentation the connectors containing the spare contacts must be carefully distributed throughout the installation.

4.1.3.6 Insertable Contact Type Connectors

Connectors that use crimp contacts, in which the contacts are both insertable and removable, are usually assembled by the user. Extreme care is necessary to prevent the contacts from being damaged. Cleanliness is also vitally important. Small pieces of insulation can easily become trapped within the connector or contact, preventing the inserted contact from seating properly. It has been estimated that improper contact seating accounts for more than one-third of all connector failures.

Connectors with insertable contacts can be assumed to be reusable. However, this is true only as long as every contact position is usable. On occasion, valuable connectors must be discarded because a contact cannot be removed from the connector.

The connectors presently being used have removable contacts that are held in place by a spring clip. The spring clip may be part of either the contact or connector. Experience has shown that connectors using a contact designed with an integrated spring clip can often be salvaged when the contact cannot be removed by ordinary procedures. The salvaging procedure requires drilling and can only be applied to the socket contact.

The process of removing a socket contact from a connector requires careful alignment of the socket and drill bits. The procedure involves drilling out the socket contact with a drill with a diameter that has been carefully selected so that the socket walls are entirely removed during drilling. Careful alignment and drill size are required to prevent damaging the insert material. The socket contact provides self-centering for the drill as the drill is slowly fed into it. After the socket contact has been drilled away, the remaining spring clip can easily be removed.

4.1.4 Procurement Considerations

Two of the most often overlooked criteria in connector selection are procurement lead time and, to a lesser extent, procurement cost. A lead time of 8 months to 1 year is not uncommon for the purchase of certain types of connectors, and during this period, prices usually increase at least once. Because of these factors (time and money), enough spare connectors and the associated contacts, shells, and so forth, should be ordered initially. An additional reason for initially purchasing adequate spares is subsequent availability. Manufacturers terminate the production of connectors, connector shells, and contacts without warning, and assess surcharges if the production line must be re-tooled. The cost of re-tooling is usually prohibitive, thus precluding the purchase of spares.

4.1.5 Connector Selection Checklist

The following factors should be considered when selecting a connector. The checklist has been compiled from a wide variety of connector brochures and specification listings and should only be used as a guide or reminder. The items are not in any special order, and some have not been discussed in the text. Further, the listing should not be considered complete. Ref. (26, 27).

- What type of connection should be used (crimping, soldering, wire wrapping or welding?)
- Will the connector seal before locking?
- What provisions are there for cable strain relief?
- Should the connector be polarized? (See Section 5.1.5 for definitions)
- What contact density should be used? What gage contact and wire?
- What environmental capabilities should the connector have?
- What type of insert material should be used?
- Does the connector demonstrate positive lock?
- Should the connector be reusable?
- Is the connector visually inspectable for correct assembly and correct installation?
- Is the connector compatible with existing in-house connector hardware?
- Is the connector compatible with existing applications (for example, quick disconnect)?
- Are the contact arrangements printed on the insert readable?
- Is there provision for safety wiring?
- Does the connector have a satisfactory history of usage?
- Are new tools required to assemble the connector?
- What is the projected delivery time?
- What is the overall cost of the connector? Is it complete in one sealed and dated package or are several purchases required to complete one connector?
- Does the connector provide a useful contact arrangement?
- What is the physical location of the connector in the system?
- Will the connector corrode, tarnish, oxidize, or contaminate easily?
- Does the connector have surfaces that can be damaged during mating?
- Does the connector design minimize the accumulation of moisture and other contaminants?
- Can the connector's shield termination requirements be met? Does the connector meet contact requirements?
- Does the connector have a standard (readily available) design?
- Does the connector have enough spare contacts to accommodate spare wires?

- Is the connector under consideration the least expensive connector that will meet all requirements?
- Is the lead time on the procurement satisfactory?

4.2 Selection of a Forced-Air Convection Cooling System

The high heat loads in closed compartments require the use of forced convection to keep equipment temperature within acceptable limits. Natural convection is not considered as useful under these environmental conditions. Forced convection transfers the heat from an object at a much faster rate than is possible by using natural convection.

The effectiveness of forced convection can be increased by providing greater surface area, fins for example, over which the air is directed. The additional heat transfer provided by fins more than offsets the slight increase in resistance due to the metallic heat flow path of the fins. The following general factors should be considered when using fins.

- a. The fins should be made of a metal that has a high thermal conductivity.
- b. The fins should either be integral with the part or bonded to the part with a good metal-to-metal contact so that there is a minimum of heat path resistance.
- c. Short, rather thick fins are more effective than long thin ones. The temperature drop from the base to the tip of a long fin may be appreciable thus tending to make the fin less effective.

Blowers used as a source of air motion for removing heat from equipment can be divided into two general applications.

- a. Blowers internal to the equipment.
- b. Blowers external to the equipment. This type may be used with open or closed equipment.

4.2.1 Factors That Influence the Choice of Blower Application

The application of a blower to the internal air circulation in pressurized or closed vented equipments is determined primarily by the equipment internal pressure and by the air flow requirements.

With pressurized equipment, the basic problem of heat removal rests primarily with the ability of the blower to provide internal circulation of the hot air so that it comes in contact with the inner surface of the case, thus effecting a heat transfer. Such blowers usually operate at a fixed speed, resulting in the same air circulation for all environmental conditions. With closed vented equipment, internal blowers with no means of speed control may be used, provided that at all environmental operating conditions the external heat dissipation from the equipment case is sufficient to prevent equipment overheating.

Since the pressure level within closed vented equipment is reduced as the altitude increases, the air flow capacity of the internal blower and its ability to improve the heat distribution within the equipment is reduced. However, if components within the equipment tend to reach their temperature limits, then a requirement for increased flow rate is necessary. Such usage is limited since at low pressure (high altitude) the blower required to maintain a mass flow of air consistent with that of a higher pressure often contributes its own heat to the significant temperature rise in the cooling air as it passes through the blower.

When blowers are used externally to supply air flow over open equipment surfaces the demands placed on the operating characteristics are considerably more severe. It is entirely possible that sufficient air flow may be unobtainable for large heat transfer requirements. Very careful evaluation of the equipment heat transfer requirements and pressure drop is necessary prior to selecting a blower. The blower should be selected on the basis of calculated air requirements at the maximum operational altitude.

4.2.2 Example - Determination of a Finned Heat Sink and Selection of a Blower (Fan)*

Airborne electronic equipment requires sufficient cooling to prevent destruction of components or degradation of performance. The most direct solution to the problem would be to determine the cooling air required for acceptable temperature rise of the equipment. However, these tests are often time consuming, cumbersome, and impractical. Another solution to the problem would be to test for

*Based on a memorandum by Leon H. Weirather, NASA Dryden Flight Research Center, Edwards, Calif., Apr. 5, 1971.

cooling requirements at laboratory ambient conditions and extrapolate to altitude. Again, this is time consuming, and the equipment is not always at hand to perform such testing.

Because of space and weight limitations, it may be desirable to pre-select the heat sink and fan for some installations. The procedure given here may be used to predict the cooling performance of these systems.

The approach suggested is directed toward the cooling of small to moderately sized $<645 \text{ cm}^2$ (100 in^2 base area) sealed electronic packages which require heat sinking for proper operation.

Assumptions

- (a) There is zero thermal resistance between the electronic package and the heat sink.
- (b) All of the heat generated by the unit is transferred to and dissipated by the heat sink.
- (c) The heat is dissipated uniformly over the heat sink.
- (d) The heat transfer is steady-state, and isothermal conditions exist.
- (e) The ambient air (cooling fluid) temperature is always less than the temperature of the heat sink.

4.2.2.1 Selecting the Heat Sink

Heat transfer by convection follows the relationship:

$$Q = hA (T_1 - T_2) \quad \text{Eq. (4.2-1)}$$

where

Q = heat dissipated, watts

h = heat transfer coefficient, $\text{W/in}^2 \text{ } ^\circ\text{C}$

A = area

T_1 = equipment temperature, $^\circ\text{C}$

T_2 = air temperature, $^\circ\text{C}$

Each material and mechanical bond or interface between the internal heat generating components and the external cooling fluid presents a thermal resistance or impedance to the heat flow. For most electronic equipment, the internal thermal characteristics are not known. However, the total amount of power to be dissipated is usually known, and an estimate can be made of the maximum allowable case temperature. If a thermal joint compound is used, the case-to-sink thermal resistance is very small for typical installations and can be ignored.

The thermal resistance (R_t) to convective heat transfer is $1/hA$ and Eq. (4.2-1) can be written:

$$Q = \frac{1}{R_t} (T_1 - T_2) \quad \text{Eq. (4.2-2)}$$

or

$$R_t = \frac{1}{Q} (T_1 - T_2) \quad \text{Eq. (4.2-3)}$$

Using the power dissipation value and the maximum allowable case temperature rise ($T_1 - T_2$), the required sea level heat-sink-to-cooling-air thermal resistance can be determined from Eq. (4.2-3).

For laminar flow, convective heat transfer varies as the square root of air density. Therefore, since

$$hA = \frac{1}{R} \sim \sqrt{\rho} \quad \text{Eq. (4.2-4)}$$

then

$$\frac{(R_t)_{alt}}{(R_t)_{SL}} = \sqrt{\frac{\rho_{SL}}{\rho_a}}$$

From the relationship of Eq. (4.2-4), the thermal resistance at the required altitude may be found.

Now, using the thermal resistance value at altitude, the required heat dissipating surface area can be determined from Figure 4.2-1. This figure shows the relationship between the heat dissipating surface area and sink-to-ambient thermal resistance for flat fin-type extrusions mounted in a vertical position. The curve is applicable for a uniform distribution of dissipated power over the sink.

Most heat sink extrusion manufacturers specify the heat dissipating surface area per unit length. After selecting the desired shape, the required extrusion length may then be determined.

The foregoing procedure for determining natural convection heat transfer is based upon laminar flow conditions. The flow may be turbulent in some installations, and the resulting "scouring" effect upon the stagnant boundary layer along the fin surfaces increases the thermal transfer to the cooling fluid. Consequently, the results obtained from the suggested approach are conservative in these cases.

At high altitudes, and especially if there is a considerable temperature difference between the equipment and the surrounding environment, radiation may have an appreciable cooling effect. It may therefore be advantageous to determine the amount of radiation cooling experienced by the heat sink selected.

If we assume that an electronics package in an aircraft compartment is a small body completely enclosed by a large body, then the amount of heat dissipated by radiation is:

$$Q = A\epsilon\sigma (T_1^4 - T_2^4) \quad \text{Eq. (4.2-5)}$$

where

Q = heat dissipated, W

A = area, cm^2 (in^2)

ϵ = emissivity of heat sink, 0.96

σ = Stefan-Boltzmann constant, $5.672 \times 10^{-12} \text{ Watt/cm}^2 \cdot \text{K}^4$
 $(3.657 \times 10^{-11} \text{ Watt/in}^2 \cdot \text{K}^4)$

T_1 = heat sink temperature, K

T_2 = air temperature, K

The area in Eq. (4.2-5) taken to be the area of the base of the heat sink since the fins contribute little additional radiative surface. An emissivity of 0.96, a value typical of painted surfaces, may be used for the heat sink. The temperature to which the sink will rise due to radiation cooling may be found by solving Equation (4.2-5) for T_1 as follows:

$$T_1 = \left(\frac{Q + A\epsilon\sigma T_2^4}{A\epsilon\sigma} \right)^{0.25} \quad \text{Eq. (4.2-6)}$$

Radiation cooling is, of course, independent of pressure or density of the air.

4.2.2.2 Selecting the Blower (Fan) and Heat Sink Combination

In some cases, the extrusion length as determined above for natural convection may be impracticably long. Forced convection cooling will then be desirable, if not mandatory. Forced air convection cooling depends primarily upon the characteristics of the air flow, fin spacing, and the degree of coupling to the air stream and is practically independent of other physical characteristics of the sink. Therefore, a reasonably sized sink, compatible with the dimensions and mounting requirements of the equipment, should be selected, and then the forced air cooling requirements are determined for this sink.

From mass transfer relationships the following may be expressed:

$$Q = K\dot{m}c_p (T_1 - T_2) \quad \text{Eq. (4.2-7)}$$

where

Q = heat dissipated, W

K = coupling efficiency

\dot{m} = air mass flow rate, lb/min

c_p = specific heat of air at constant pressure,
 0.2 calories/gram/°C $(7.62 \text{ W-min/lb}^\circ\text{C})$

T_1 = heat sink temperature, °C

T_2 = air temperature, °C

The coupling efficiency (K) is 0.2 for wide spaced fins and 0.6 for close-spaced fins. An intermediate value of 0.4 will be satisfactory in most cases. The specific heat of air at constant pressure (c_p) can be considered constant for the altitude ranges normally encountered by flight test aircraft.

It is seen from Eq. (4.2-7) that heat transfer is directly proportional to mass flow. However, fans are volumetric devices; i.e., for a given speed a fan delivers a constant volume of air per unit time regardless of the air density. Therefore, a fan must be the proper size to deliver the required mass flow at all operating conditions. The fan must be capable of delivering a maximum volumetric flow rate which occurs at the highest altitude at which the fan is to operate.

The air mass flow rate required to keep the equipment temperature rise at the allowable level is found from:

$$\dot{m} = \frac{Q}{Kc_p (T_1 - T_2)} \quad \text{Eq. (4.2-8)}$$

The required volumetric flow rate may then be determined from:

$$\dot{V} = \frac{\dot{m}}{\rho_a} \quad \text{Eq. (4.2-9)}$$

where

\dot{V} = volumetric flow rate

\dot{m} = mass flow rate

ρ_a = density of air at altitude

Selection of the correct fan requires knowing the pressure drop associated with the flow passing through the system. Finned heat sinks (air flow parallel to the fins) present very little impedance to the air flow, and the pressure drop is small. A typical sea level pressure drop for this type of configuration is 0.5 centimeter (0.2 inch) H_2O .

Using the maximum volumetric flow rate required (at maximum altitude) as determined from Eq. (4.2-9) and the sea level pressure drop, we may now select a fan from manufacturer's catalogs. Fan performance data are usually published for standard sea level conditions. We may assume that maximum volumetric flow as determined above for maximum altitude will be the same at sea level for conventional constant-speed fans. Thus, the usual catalog data may be used for fan selection. For airborne applications, it is usually advantageous to select a 400 Hz ac fan. These fans are physically smaller and have greater shaft speeds than 60 Hz and dc powered units.

Special types of fans are available for high altitude applications. In these fans the shaft speed varies inversely with the air density, thus delivering a greater mass flow at low densities than can be obtained with constant-speed devices. Another advantage of these types is that they require less power at low altitudes than conventional fans. Performance data for the high altitude fans are usually given in terms of mass flow, altitude (density), and pressure drop, as well as the standard sea level performance curves.

In most cases of forced convection, the effects of radiation and natural convection are relatively small (as compared to forced convection) and may be disregarded. However, the effects of the various modes of cooling may be combined, if so desired.

4.2.2.3 Checklist for Selecting a Heat Sink and/or Blower (Fan)

The steps required to select a finned heat sink extrusion and/or a fan to cool airborne electronic equipment are summarized below:

(1) Using the known value of heat dissipation and the maximum allowable temperature rise, find the sea level thermal resistance to natural convection from Eq. (4.2-3).

(2) Find the thermal resistance at the required altitude from Eq. (4.2-4).

(3) From Figure 4.2-1, find the heat dissipating surface area required to obtain the thermal resistance at altitude.

(4) Select an extrusion of the desired shape from the manufacturer's catalog, and determine the length necessary to provide the required heat dissipating surface area.

(5) Determine the cooling by radiation (if desired) from Eq. (4.2-6).

(6) Combine the effects of natural convection and radiation (if desired).

If it is found that natural convection and radiation heat transfer are insufficient to cool the equipment with a reasonably sized sink, proceed with the following steps:

(7) Select a sink sized to the dimensions and mounting requirements of the equipment.

(8) Find the air mass flow rate necessary to keep the equipment temperature rise to the acceptable value from Eq. (4.2-8).

(9) Determine the volumetric flow rate at the maximum altitude from Eq. (4.2-9).

(10) Assuming a sea level pressure drop of 0.5 centimeter (0.2 inch) H_2O , select the fan to meet the requirements of (8) and (9) above.

(11) Combine the effects of the various modes of cooling (if desired).

The technique described provides only an estimate of the cooling requirements for an airborne electronic unit. The accuracy of the technique obviously is dependent upon the validity of the assumptions made and upon the accuracy of the estimates of the true conditions. No attempt has been made to determine the errors involved.

This relatively straightforward approach can be easily and quickly used by technical personnel to obtain estimates of cooling requirements. If the electronic unit is known to be operating near its temperature limits or if the unit is essential to the mission, laboratory tests should be performed under simulated environmental conditions to determine the adequacy of the cooling.

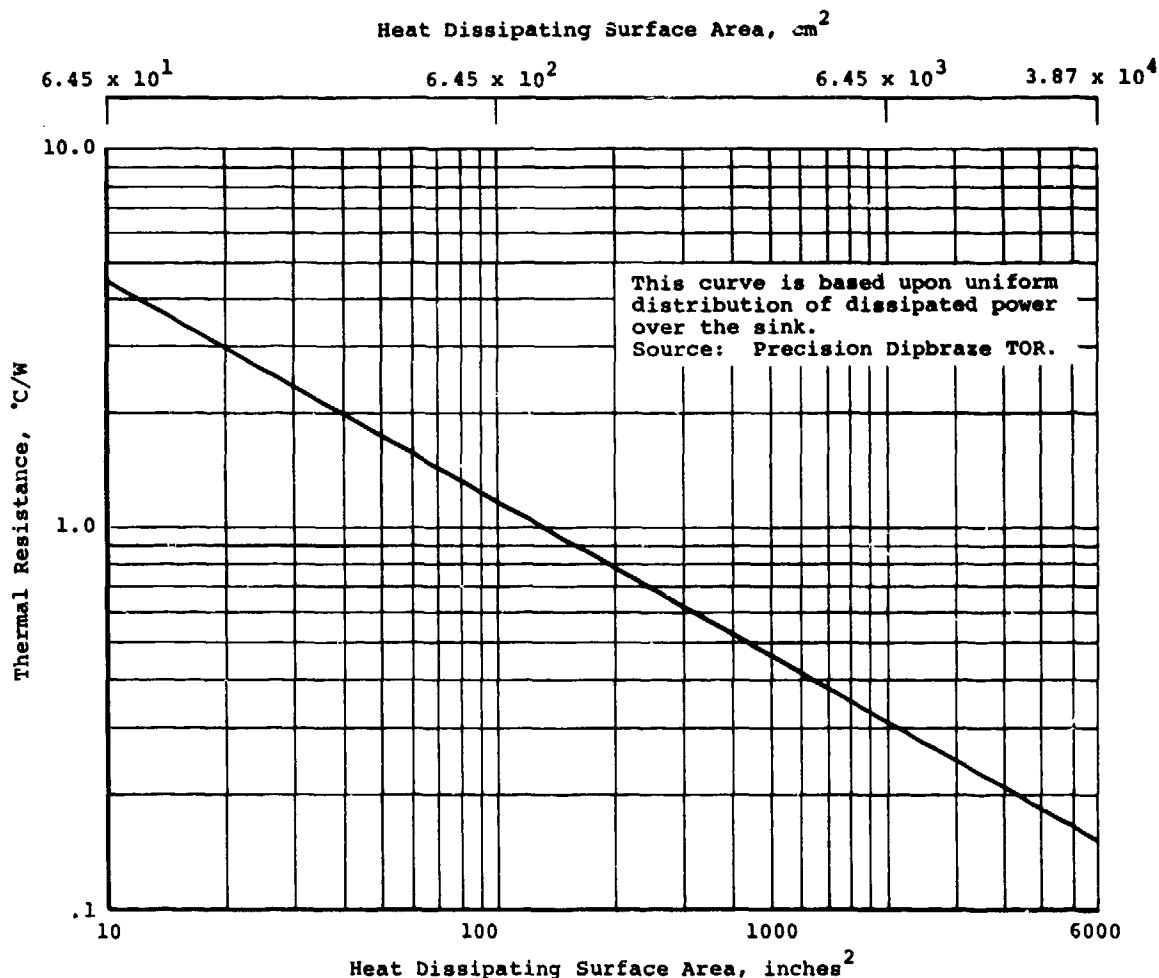


Figure 4.2-1. Thermal Resistance Vs Surface Area for Flat Vertical Fin Type Extrusions.

4.3 Selection of Mechanical Isolators

Depending on the type of flight vehicle, the mission profile will vary and thus be a factor in the selection of isolators. The different classification of aerospace vehicles include airplanes and helicopters. There are a variety of differences in the design of these vehicles and the flexibility of wings, tail surfaces, and the fuselage will vary. Each type of flight vehicle has a different response to excitations from its mission profile. Further, different responses are introduced by the type of engines used. Different excitations are produced by reciprocating engines, turbo props, turbojets, ram jets, etc. While isolators are selected mainly for protection against vibration, the shock environment must also be considered.

Generally, the most severe shock occurs during landing and booster-assisted or catapult assisted takeoffs. The direction of shock is as important as the intensity. Highly maneuverable aircraft spend a considerable length of time in such attitudes as climbing, diving, loops and rolls. Because of this, the aircraft attitude should also be considered when selecting an isolator.

The selection of isolators and the isolation mounting system is dependent mainly on the space available for both the isolation system and the expected sway or displacement of the equipment. For example, if the space available warrants that an equipment be higher than it is wide, resulting in a high center of gravity, then a bottom-mounting system should be used with stabilizers. Other factors to be considered are the shock and vibration environment, including the excitation frequencies, the stiffness of the supporting structure and the environmental design limitations of the equipment itself. Ref. (B2).

Equipment in an aircraft is subjected to shock and vibration in all directions. This requires a six-degree-of-freedom system with translational movement in the vertical, longitudinal and lateral directions as well as rotational movement about these three axis. The six degrees of freedom are shown in Figure 4.3-1. An installed item of equipment will have a natural frequency in each of these axis and each must be considered when designing the isolation system. For example, if isolators of equal stiffness are located unsymmetrically about the center of gravity of an equipment, certain of the translational and rotational modes will couple. Stated another way, when coupled, vibration cannot exist in one mode without existing in its coupled mode. Thus, a horizontal force through the center of gravity will not only displace the equipment horizontally, but it will cause it to rotate.

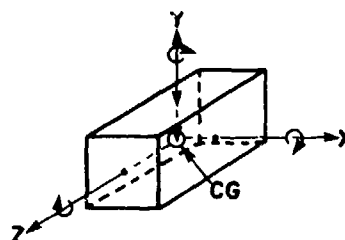
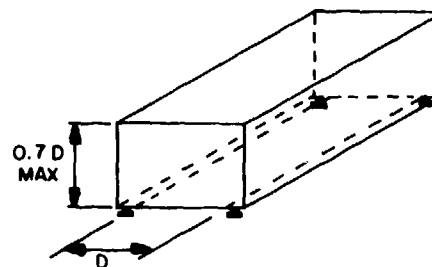
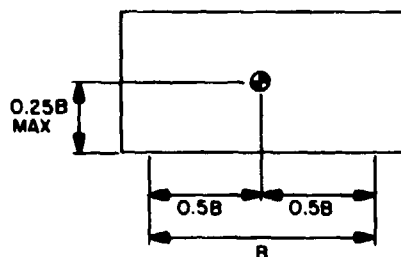


Figure 4.3-1. Six-Degrees-of-Freedom System about the Center of Gravity.

Each coupled mode has its own frequency and it must be considered in the basic design. Isolators may be arranged in a variety of mountings, but in general all the variations can be grouped into a few basic types, and/or combinations. Typical examples are shown in Figure 4.3-2, (a) through (e).



(a) Underneath Mounting System Showing Design Dimensions.

Figure 4.3-2. Basic Isolator Mounting Systems

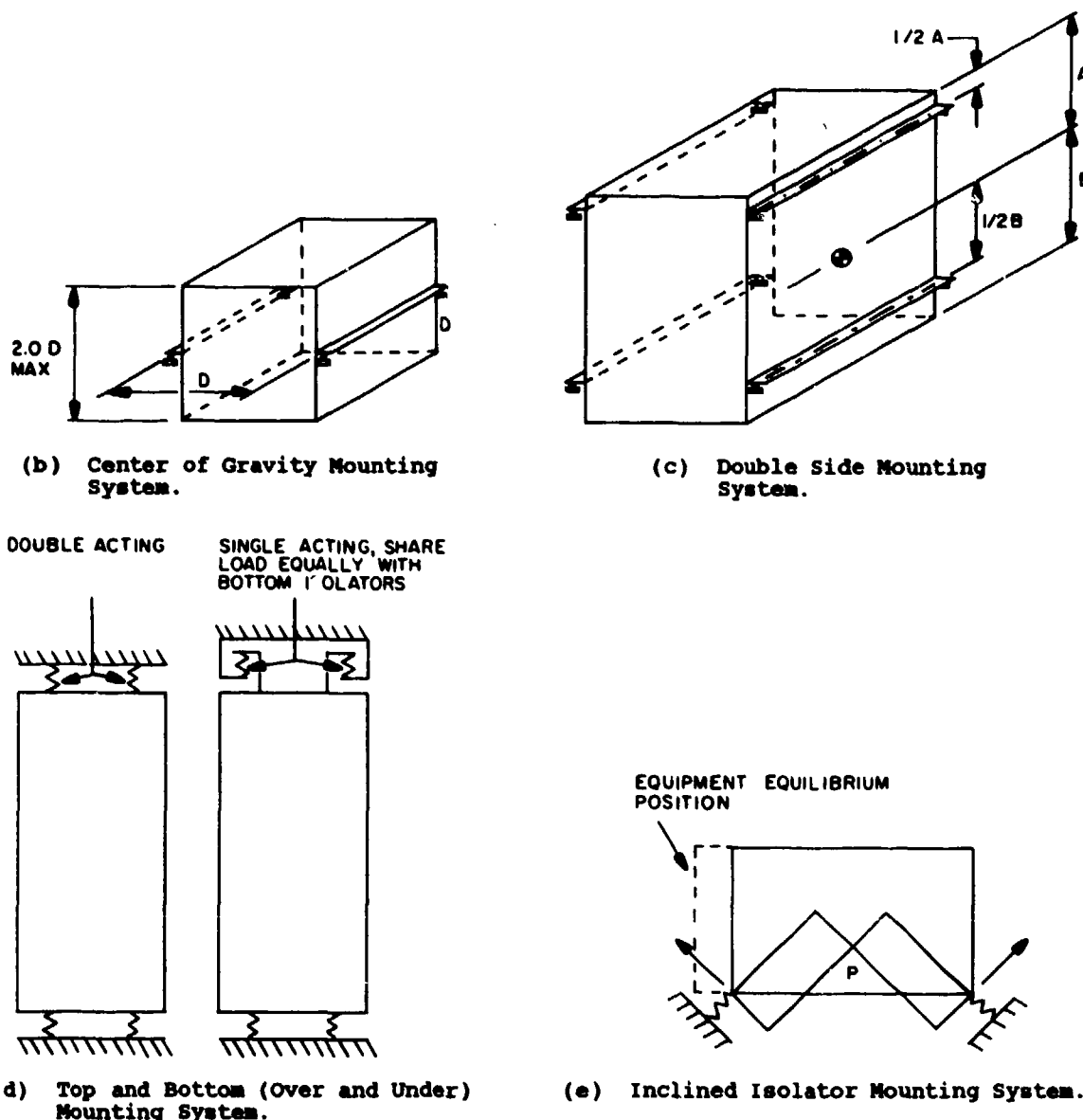


Figure 4.3-2. Concluded.

4.3.1 Underneath Mounting System

The underneath mounting system is the most widely used, since most chassis configurations are suitable for this application and there are less limiting requirements. This system is used in applications where the distance from the base to the center of gravity of the supported equipment does not exceed isolator spacing by a ratio greater than 0.25. This relationship is necessary to maintain required stability and isolation. Figure 4.3-2(a) illustrates the design dimensions for equipment having a uniform density. The center-of-gravity height to isolator spacing ratio limits the use of the underneath system for narrow axis equipment. However, in most applications the height of the center of gravity seldom exceeds 0.36 of the overall height of the equipment. This permits equipment having ratios of equipment height to isolator spacing up to 0.7 to be mounted in this manner. Choosing the proper isolators for an underneath-mounted rectangular object is relatively simple. The total weight is divided by four; then the appropriate isolator is selected, and placed at the four corners. However, if the center of gravity of the equipment is located unsymmetrically in the horizontal direction, the isolators at each corner will be different. The load on each isolator can be calculated by using the following formulas and Figure 4.3-3. W is the weight of the equipment with connectors and cables attached.

$$\text{Load on isolator 1} = W \left(\frac{A_1}{A_1 + A_2} \right) \left(\frac{B_2}{B_1 + B_2} \right) \quad \text{Eq. (4.3-1)}$$

$$\text{Load on isolator 2} = W \left(\frac{A_1}{A_1 + A_2} \right) \left(\frac{B_2}{B_1 + B_2} \right) \quad \text{Eq. (4.3-2)}$$

$$\text{Load on isolator 3} = W \left(\frac{A_1}{A_1 + A_2} \right) \left(\frac{B_1}{B_1 + B_2} \right) \quad \text{Eq. (4.3-3)}$$

$$\text{Load on isolator 4} = W \left(\frac{A_2}{A_1 + A_2} \right) \left(\frac{B_1}{B_1 + B_2} \right) \quad \text{Eq. (4.3-4)}$$

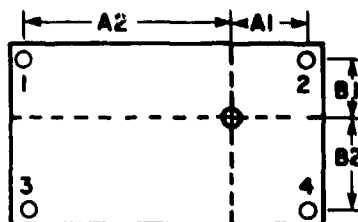


Figure 4.3-3 Load Determination Dimensions.

4.3.2 Center-of-Gravity Mounting Systems

In center-of-gravity mounting systems, the isolators are located in a plane that passes through the center of gravity of the mounted equipment, as shown in Figure 4.3-2(b). It is a refinement of the underneath mounting system in that while coupling of certain rotational and horizontal modes in the underneath system is unavoidable because of the unsymmetrical placing of the isolators relative to the horizontal plane through the center of gravity, these same modes are always decoupled in center-of-gravity systems. With coupled modes, the spread between natural frequencies of a system is greater, reducing isolation efficiency. If the highest natural frequency of the mounting system is set well below the forcing frequency, it may put the lowest frequency at a level that introduces instability in the system.

4.3.3 Double Side Mounting Systems

Double side mounting systems, also called double-level side mounting, are normally used on equipments that have a height-to-width ratio greater than two and a tendency for excessive flexing. Eight isolators are used, with four each placed symmetrically on opposing sides of the equipment so that the figure formed by the isolators is a cube. The double side mounting system is shown in Figure 4.3-2(c). The extra isolators provide additional support points that distribute the load more equally to the chassis. In addition to being used for equipment with a height-to-width ratio greater than two, the double side mounting system should be used for very heavy equipment from a safety standpoint. With attachment points near the top and bottom of the equipment, it is more secure than the other systems. In fact, satisfactory results have been obtained with equipment having a height-to-width ratio up to five. The maximum limit of this system is reached when the structural rigidity of the equipment allows excessive bending to take place.

4.3.4 Over-and-Under Mounting Systems

In an over-and-under mounting system eight isolators are used, but instead of being mounted at the sides of the equipment as in a double side mounting system, the mounts are placed at the top and bottom of the equipment. This system is used when the space for the equipment provides an overhead support to which the isolators can be fastened. This system is also useful when the height-to-width ratio of the equipment exceeds one and a half, so that a bottom-mounted installation would tend to be unstable. Most of the discussion about the double side mounting system applies to this system. In the over-and-under mounting system, the mounts located at the top of the equipment carry an equal share of the load with the bottom mounts. To do this, double-acting mounts are used, or the isolators are mounted so that they support the equipment as do the bottom mounts. Figure 4.3-2(d) shows the over-and-under mounting system, with two ways of mounting the top isolators.

4.3.5 Inclined Isolator Mounting System

When four isolators are used and they cannot be located in a plane through the center of gravity, decoupling can be accomplished by inclining the isolators, as shown in Figure 4.3-2(e). When equipment is bottom mounted coupling occurs between translational modes because of the unsymmetrical position of the isolators relative to a horizontal plane through the center of gravity. This dissymmetry causes external forces from the isolator horizontal stiffness, to apply a turning moment to the equipment when the equipment is displaced sideways. However, if the isolators are inclined instead of being placed vertically, motion along either of the principal axes results in deflection of the isolators in both the radial and axial directions. Because the isolators are inclined, the usual reference of horizontal and vertical is changed to radial and axial. In this system, a translational motion results in external forces from both the radial and axial isolator stiffness. The angle of isolator inclination and the isolator horizontal and vertical stiffnesses are quite critical in this mounting system. It is a special purpose application of isolators and requires detailed analysis to operate successfully.

4.4 Selection of Displays and Controls for Crew Area

Aircrew instrumentation displays and controls require an understanding of the information to be presented and of the methods that most effectively transfer this information into correct control actions. Displays must suit the particular conditions of use and be converted into inputs that humans can perceive. Accordingly, lights, indicators, and other displays are used as methods to present information to the operator.

To provide the proper displays it is necessary to consider viewing distance, level of area illumination, instrument lighting (indirect, flood, edge and rear). The selection of displays must be based upon evaluation of the advantages and disadvantages of indicators, scales, numeral style and size, color and shape coding, labeling, zone marking, etc. The controls for these displays must logically relate to the display being controlled by providing specific control function and display flexibility. Refs. (B7, 28, 29, 30).

4.4.1 Displays

The instrumentation engineer must know the total number of controls and displays required to present essential information to the operator. In general, for aircraft circumstances the visual sense is the most suitable input channel for system status information.

The instrumentation engineer/designer of a visual display must determine the purpose and the conditions under which a specific display is to be used. The conditions (cramped cockpit) and purpose (warning panel) often dictate the shape, size, and location of these displays. Operational conditions which must be considered include the viewing distance, illumination, angle of view, adjacent displays, arm-length distance, and cockpit control panel compatibility. Also to be considered is whether or not a cockpit camera is to be used to record instrument panel readings.

The best viewing area is located directly in front of the crew member, but this is the area where mission related instruments are clustered. In general, the instrumentation engineer is given areas located at the periphery of the field of view and/or the area located between the crew members' knees. These particular areas create a definite design challenge for the instrumentation engineer. In consideration of these cockpit areas, the engineer must ensure that all display details are continually in the field of vision; free of excessive parallax; free from light reflections; and visible in bright sunlight.

If cockpit cameras are used to monitor portions of the cockpit panel, the size and type of the display details must be compatible with the lowest expected light level as well as the image resolution and granularity of the photographic film. Lighting due to direct sunlight should be considered and resulting high contrast of details minimized.

The design and spatial placement of displays and controls should make it easy for the operator to select the proper control and operate it in the correct manner.

The instrumentation engineer (designer) must also determine what the operator's reaction is going to be towards the controls and displays. For example, precise, stable information is better displayed by a digital readout rather than a meter/needle readout. The digital readout is faster and will be read accurately more often than other type meter displays. However, because of familiarity the pilot oftentimes prefers the round D'Arsonval type display.

4.4.1.1 Indicator and Status Lights

Lights are often used to convey routine information and to warn of dangerous conditions, or to call attention to malfunctions. The effectiveness of a signal light depends upon its color, its brightness, and location. In addition, it must be intense enough to provide adequate contrast in ambient illumination. The total number of colors used for lights should be kept to a minimum and the designer must select color combinations which prevent confusion, such as yellow and amber. These colors tend to change with age and when illuminated by a high intensity bulb may look alike. Recommended colors are green, amber, red, white, and blue.

In determining any color of a display the designer should try to match standard concepts and previously-established standards. Table 4.4-1 below relates colors to typical functions.

Table 4.4-1 Lamp Colors and Their Related Functions

COLOR	FUNCTION
Red	Stop; Danger; Warning; Emergency
Green	Go; Power ON; OK; Proceed
Amber	Standby; Caution; Intermediate steps
White	Routine Operating Conditions
Blue	Auxiliary Data; Information

Since most signal alarm lights are normally re-set, a press-to-test feature should be provided for testing all the lamps.

When control panels are located out of the field of direct view, a master warning light located directly in the operator's field of view is necessary so that the operator may direct his attention to these peripheral areas. Ideally, every signal lamp is clearly identified.

4.4.1.2 Labels

Various research efforts have been conducted to determine what factors give the greatest legibility of printed material. Although these results are not entirely consistent, it is possible to generalize on some of the conclusions.

The legibility of characters is affected by contrast between character and background, character height, ratio of character height to width, and ratio of height to line width. The following recommendations are given for good legibility:

1. Panels and dials should have white lettering on a dark (or black) background in aircraft.
2. A height-to-width ratio of 3 to 2 is recommended for characters on panels and scales.
3. For white characters on a black background, the best legibility is given by a line width of $1/7$ to $1/8$ the character height. If black characters on white background must be used, the lines should be about $1/6$ the character height.

The sizes and spacings of lettering must be increased proportionally with greater viewing distances and lower lighting levels.

4.4.1.3 Panel Meters

The D'Arsonval meter movement is very popular because of its basic simplicity, inherent response characteristics, basic analog compatibility and history of usage. Although modified versions of this type of meter (servometric meter) improve its accuracy and minimize vibration-induced pointer movement, this modification does have certain undesirable features:

1. Requires a separate power in addition to the signal input.
2. Positive indication of meter failure or loss of input is more difficult to determine. (The standard D'Arsonval meter drops off scale with loss of signal.) The servometric meter, however, leaves the pointer at its last position.

Although a wide variety of multiple movement meters exist, the poor readability of the smaller multiple scales cancel any advantages gained. For nearly all purposes the circular meter is the best choice.

4.4.2 Controls

The proper selection of a control device for a specific purpose requires a complete understanding of the function and purpose of the control, what it controls, and its relative importance to other controls. Careful consideration must also be given to the information required by the crew member in locating, identifying, and using the control. In addition, any limitations imposed by constraints on the crew member should also be considered.

4.4.2.1 Toggle Switches

The most frequently used control device is the toggle switch. Some of the factors which dictate this selection are that toggle switches require little panel space, visually indicate status (except momentary switches), and are easy to activate during a wide variety of flight conditions. Functions utilizing momentary switches in most cases require a status indicator located in the vicinity of the switch.

For situations which require wearing gloves a wedge-shaped tab handle provides a large grasping area with which to actuate a toggle switch. One advantage of the larger wedge-shaped handle is its length which increases the operator's mechanical advantage during activation. One obvious disadvantage is its minimum deflection angles for a three-position switch.

4.4.2.2 Push Button Switches

In general push button switches are used for applications requiring rapid initiation of a function, for high-frequency-of-use situations and for applications requiring positive visual response.

For circumstances when the identifying legends are a part of an illuminated push button, the use of the larger size push button (2.0 centimeters, 0.8 inch) should be considered. If two or more push button type switches are mounted side by side, barriers should be inserted between them to limit the finger movement during switch actuation.

4.4.2.3 Rotary Switches

Rotary switches are usually employed when four or more detent positions are required. As a multiple switch the rotary switch is generally more suitable for high currents than the toggle switch. However, as the number of detent positions increases the possibility of selecting an incorrect position also increases. Similarly, if the rotary mechanism jams, all other switch functions are inhibited. For this reason critical functions are better left to toggle switches.

4.4.2.4 Selecting Controls

In selecting the instrumentation controls and their size and location, the engineer must consider the effects of flight clothing. Particular attention should be directed at restricted arm movement due to heavy clothing and the size of the control based on its actuation with a gloved hand or finger (if required).

After reviewing the control requirements, the engineer should take into consideration the following suggestions:

1. Select controls having motions compatible with those of the display. For example: a toggle switch thrown up should be in the ON position; a knob turned clockwise should increase the quantity it controls (slide switches from left to right or from bottom to top).
2. Select either a linear control or a rotary control for making a small adjustment over a short range. If the range of adjustment is large, a multi-revolution rotary control is desirable.
3. For adjustments which are made in a limited number of discrete steps, consider a detented control for a rapid and easy operation.
4. Position controls (knob, push buttons and switches) a sufficient distance apart to preclude operator interference with adjacent controls when the operator wears gloves.
5. Select controls for ease of identification by physical feel and operational position.
6. Try to keep the quantity of controls to a minimum.
7. Select controls that provide the operator with a positive feel or visual indication assuring that switching has occurred.

One of the important considerations in the relationship between displays and controls is the control-display ratio. A small turn of the knob should result in a small response from the knob's movement. An additional point is that an operator under heavy stress may forget an "unnatural" relationship of control function and revert to the "natural" one, (item 1. above, for example), causing system failure or loss of data.

There are some controls which must not be operated except at the right moment. Controls of this kind can be guarded by recessing, by use of hinged safety covers, by careful out-of-the-way location, by screw-driver adjust, or by locking devices.

4.5 Selecting Fuses and Circuit Breakers

Either fuses or circuit breakers may be used for circuit protection; however, circuit breakers are preferable on any circuit whose failure affects the safety of flight. This preference is primarily due to the fact that resetting a circuit breaker is generally safer and quicker than changing a fuse.

At the instrumentation-bus level where the total current requirements are in the tens-of-amperes, circuit breakers are used for a combination of purposes, e.g. as on-off switches. If and when a fault occurs it is usually at the sub-system level and the circuit breaker provides convenient on-off capabilities to de-energize the instrumentation bus. However, fuses provide a wide range of ratings and trip characteristics not available in circuit breakers. At the sub-system level then fuses can offer these advantages:

1. Economy with low weight and volume.
2. Ease of design and installation of fuse boxes.
3. Availability in a wide variety of ranges below one ampere.

Whenever the circuit design mixes circuit breakers and fuses, careful attention must be given to insure proper coordination of system protection.

From an environmental point of view, fuses and circuit breakers can be affected by a combination of shock, vibration, and temperature. Thus engineering care must be exercised in the selection of both fuses and circuit breakers, their location and installation. Ref. (31).

The fundamental design philosophy of aircraft instrumentation wiring should include automatic protection that will isolate a wiring fault to a single circuit. The primary consideration should be the protection of the instrumentation wiring so that the danger of smoke, fire, and toxic fumes is minimized. Further, the circuit protection must be designed so that any fault occurring in one circuit does not affect other operational circuits. This objective can usually be achieved by using the proper circuit protective devices, proper wiring sizes, and careful circuit design.

The choice between circuit breakers, fuses, limiters, or other protective means is influenced by several factors:

1. Characteristics of the protective device.
2. Replacement of the protective device after failure.
3. Physical and environmental constraints.
4. Circuit application.

When to use a circuit protection device:

1. For any wire length carrying current which may cause the wire to act as a fuse.
2. A circuit protection device should be used whenever a conductor diameter is reduced to a smaller diameter conductor.

4.5.1 Fuses

A fuse is a strip of metal having a very low melting point. The metal strip can be made of lead, lead and tin, tin and bismuth or some other low-melting-temperature alloy. It is placed in a circuit in series with the load so that all load current must flow through it.

When the current through a fuse exceeds the capacity of the fuse, the metal strip melts and breaks the circuit. The strip must have low resistance and yet it must melt at a comparatively low temperature. When the strip melts, it should not give off a vapor or gas which will serve as a good conductor since this could sustain an arc between the melted ends of the metal strip. The metal alloy used must be of a type which reduces the tendency toward arcing.

Fuses are generally enclosed in glass or some other heat-resistant insulating material to prevent an arc from causing damage to the electrical equipment or to parts of the aircraft. Fuses used in aircraft are mechanically classified as cartridge type, plug-in type, or clip type. Each of these types are easily removed, inspected, and replaced. Refs. (32, 33).

4.5.1.1 Fuse Types

Three basic type of fuses will be considered.
(Consult the manufacturer for specific applications).

1. Normal Fuse - This type may or may not be current limiting. Normal fuses contain a single element and possess a time-current characteristic curve which is smooth without discontinuities. (See Figure 4.5-1)

2. **Time-Delay Fuses** - Time-delay fuses may or may not be current limiting. These fuses are often referred to as "dual-element" in that they are designed with two elements: a thermal cutout with very high time-lag characteristics which accommodate transient overloads but "fuses" on continuous light overloads, and an element which "fuses" only on heavy overloads or short circuits. The thermal cutout is designed to pass momentary surges such as motor starting and switching transients. The time-current characteristics show a non-uniform curve with considerable time-lag. (See Figure 4.5-1).
3. **Very Fast-Acting Fuses** - These fuses do not have a time-delay feature as they are designed to be extremely fast during short-circuit conditions. Very fast acting fuses are designed to protect semiconductor circuitry because of their fast response to overload currents.

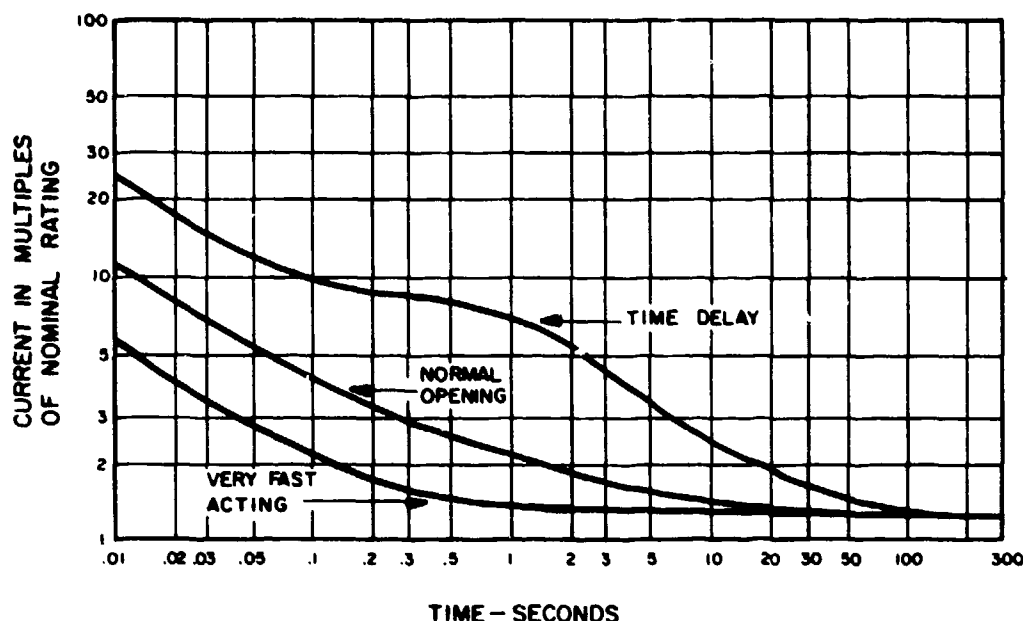


Figure 4.5-1 Comparison of Very Fast-Acting, Time-Delay and Normal Opening Type Fuses of Identical Current Rating.

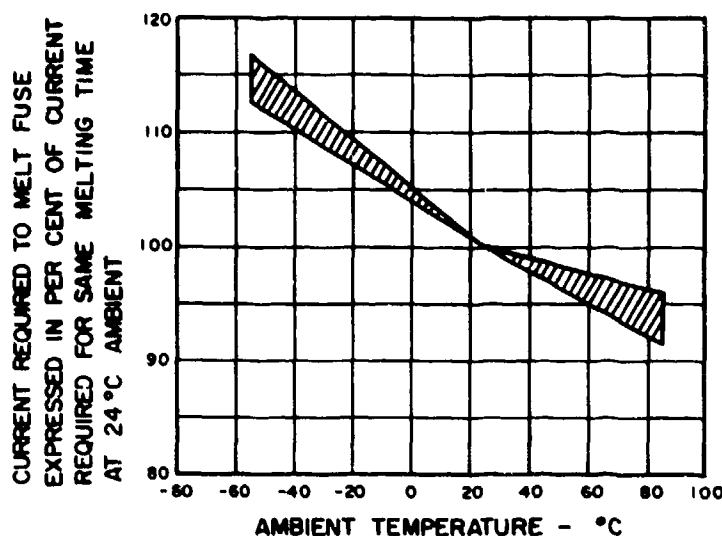


Figure 4.5-2 Effect of Temperature on Very Fast-Acting and Normal Opening Fuse Operating Characteristics.

These fuses may or may not be current-limiting. (See Figure 4.5-2). For a fuse to be current limiting, the fuse under short-circuit conditions must limit the instantaneous peak current to a value less than that which would flow if the fuse were not in the circuit.

4.5.1.2 Fuse Ratings (Standard Definitions)

Fuses are rated according to current, voltage and interrupting capacity.

4.5.1.2.1 Current

Generally, all types of fuses must be capable of carrying 110% of their rated current in free air at room ambient temperature until thermal equilibrium is established. These types are required to open within one hour at 135% current load. Time-delay type fuses are further required to hold for a minimum of 12 seconds at 200%. Cartridge type time-delay fuses are available which will hold for 10 seconds at 500%. The current rating of all types of fuses will be affected by ambient temperature.

4.5.1.2.2 Voltage

The voltage rating stated for a fuse is the maximum rms ac and/or dc voltage at which the fuse is designed to operate. Fuses can be used for any voltage less than the maximum rating.

4.5.1.2.3 Interrupt Capacity

This defines the maximum current at rated voltage that the fuse can safely interrupt where the recovery voltage does not exceed the rated voltage. (Recovery voltage is defined as the voltage impressed across the protective device after the circuit has been interrupted and after the high frequency transients have subsided.)

4.5.1.3 Environmental Considerations

The following conditions should be reviewed and used as a basis for fuse evaluation.

1. Temperature: Figure 4.5-2 shows the effect of temperature on the operating characteristics for very fast-acting, time-delay and normal opening fuses. Time-delay fuses are more sensitive to temperature environment because of the thermal cutout element.
2. Altitude: Up to altitudes of 21,340 meters (70,000 feet) the interrupting rating of a fuse is usually not affected. The altitude data is actually based upon the ambient temperature at maximum altitude; thus, altitude derating is based upon temperature rather than ambient pressure.
3. Atmospheric: Most atmospheric environments do not pose any problems for fuses. In a corrosive environment it is suggested that all ferrules, fuse-holders, fuse blocks, etc., be plated. In addition, suitable housings should be constructed to protect fusing elements from corrosive liquids.
4. Shock and Vibration: Fuses for Mil-Standard operation are evaluated for both 100% rated current and no current conditions, as specified by MIL-STD-202. In general, the typical fuse used by the instrumentation engineer is evaluated at cycles of 5 to 2000 per second, and accelerations up to 30g or with displacements up to 1.27 centimeters (0.5 inch) double amplitude.

4.5.1.4 Fuse Selection

Normal and very fast-acting fuses should be sized to adequately protect wiring and should not be continuously loaded in excess of 80% of the fuse ratings. Characteristics of the time-delay fuses allow them to be sized closer to the current load. However, circuit conditions should be thoroughly investigated before making such a decision to prevent unnecessary fusing action.

Depending on the ambient temperature at the fuse location, the current rating of the fuse may have to be derated or uprated. Nominal ratings (as marked on the fuse) are for an average temperature of 24° C (75° F), although this value may vary with different manufacturers. If the fuse must operate at higher ambient temperatures, a larger nominal rating must be specified to compensate for the difference in ambient heat. The opposite is true in a colder ambient area.

Most components can be adequately protected from overcurrents and short-circuit by selecting the proper fuse. The prime factor to be considered is current limitation. It is important to limit this current to as small a value as possible since damaging thermal and magnetic energies vary with the square of the current.

For flight critical circuits in non-piloted vehicles, for example, it is essential that the fuse be of the highest rating possible consistent with cable protection. These circuits should be carefully engineered to take cognizance of the cable-fuse combination ensuring that short-time transients do not cause circuit faulting. Non-critical circuits can be fused on the basis of the lowest rating consistent with reliable equipment operation. Careful engineering and testing is recommended to demonstrate the effectiveness of such protection under flight conditions.

Fuses, particularly high-capacity units, dissipate considerable energy and their installation should allow for heat rejection so that the temperature rise of the fuse does not exceed that of the cable. Excessive rise in temperature of the fuse itself can change the desired time-current protection rating of the fuse and alter the initial cable protection design. Care should and must be taken in dispersing the heat since adjacent equipment can likewise be affected.

4.5.1.4.1 Short Circuit Wire Protection

Manufacturer's charts are available that relate maximum time-current capabilities of wire types. A typical chart will depict the amount of short-circuit current that the conductor can safely withstand. If the short circuit current available during failure exceeds the conductor specifications, the protective device then has the task of current-limiting. Time-delay, normal, and fast-acting current-limiting fuses are available which will protect wires from this type of damage.

4.5.1.4.2 Motor Protection

Due to motor starting transients, time-delay type fuses are recommended for the protection of motor circuits. Because of their inherent delay, time-delay fuses can be sized close to the full load rating of the motor, thereby preventing motor burnouts which might otherwise occur from overloads. If dual-element time-delay fuses are used for motor protection they should be sized at 125% or less of the full load rating of the motor.

The types of motors for use in aircraft instrumentation require careful individual analysis for each application to assure compatibility with their protective devices.

4.5.1.4.3 Rectifiers, Semiconductors

Very fast-acting, current-limiting fuses are recommended for protection of rectifiers and solid state components where the available fault current must be limited to a value which the component can safely withstand. Generally, knowing the ampere-squared-seconds and the peak half-cycle current limitations is sufficient to select the proper current-limiting fuse and assure protection.

4.5.1.4.4 Fuse Resistance and Voltage Drop

One important factor that is often overlooked when selecting a very fast acting fuse is its resistance and voltage drop. Some typical values are presented in Table 4.5-1. The cold resistance is measured at 10% or less of rated current. The hot resistance is measured at 100% of rated current after 5 minutes. These resistance values can be used as a guide but the actual resistance of any individual fuse may vary due to manufacturer's tolerances and the degree of loading of the fuse.

Table 4.5-1 Resistance and Voltage Drops Across Small Fuses.

VERY FAST ACTING FUSES				
Ampere Rating	Cold Resistance	Hot Resistance	Average Resistance	Voltage Drop at Rated Current
Approximate Ohms				
1/100	150	310	263	2.63
1/32	24	83	40.0	1.25
1/16	6.6	10.6	6.9	0.43
1/8	1.6	3.1	6.0	0.75
1/4	2.9	9.6	4.7	1.18
3/8	1.9	10.5	3.0	1.13
1/2	1.0	4.3	2.7	1.4
3/4	0.78	4.7	2.0	1.5
1	0.35	0.75	0.24	0.24
1-1/2			0.13	0.20
2			0.10	0.20
3			0.06	0.18

Instrumentation systems routinely use precision voltages of five volts or less. As shown in the table under the column titled, "Voltage Drop at Rated Current" it is evident that precision voltage values can be compromised by careless fuse selection.

4.5.1.5 Fuse Coordination

Coordination defines the ability of the protector with the lowest rating, to open before protectors with higher ratings open.

Isolation of a faulted circuit to the point of origin is very desirable in any power system. Aircraft in particular cannot tolerate nuisance outages. Properly selected fuses will coordinate with one another throughout overload to short-circuit currents. Figure 4.5-3 shows a typical protective device coordination. Fuses A and B will coordinate with each other if, and only if, the total clearing energy of the downstream fuse B is less than the melting energy of the upstream

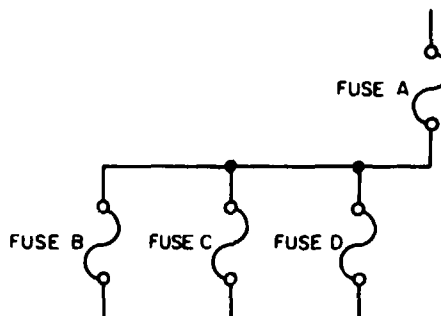


Figure 4.5-3 Fuse Coordination

fuse A when C and D carry their normal currents. Fuses C and D should be individually coordinated also.

4.5.2 Circuit Breakers

A circuit breaker as used in an aircraft is constructed to be capable of automatic circuit interruption under fault conditions and also capable of repeatedly performing this function when the defined set of fault conditions occur. In general these devices are used for cable protection and should be selected to match the thermal characteristics of the cable. Circuit breakers are designed for frequent operation and are often used as emergency switches. Refs. (34, 35, 36).

4.5.2.1 Circuit Breaker Types

Circuit breakers are classified according to their method of operation as thermal, magnetic, or combined thermal-magnetic. Further, circuit breakers may be "trip-free" or "non-trip-free." A non trip-free circuit breaker is so designed that the circuit can be manually held closed when carrying overload current that would automatically trip the breaker to the open position. (Not recommended for aircraft use). A trip-free circuit breaker is so designed that the contacts of the circuit breaker cannot be held closed when carrying overload currents that would automatically trip the breaker to the open position. None of the circuit breaker contacts will reclose while the operating mechanism is held in the closed position. (Used for aircraft applications.)

4.5.2.2 Circuit Breaker Ratings

Circuit breakers are rated for continuous current carrying capacity, maximum interrupting capacity and operating voltage of the system(s) in which they are to operate.

Aircraft circuit breakers are generally designed for 28 volt dc circuits and 115/200 volt 400 Hz ac circuits. In the case of magnetic breakers, however, the trip time may be different for ac and dc circuits. Thermal breaker trip time is dependent on current and ambient temperature and is independent of voltage. Circuit breakers are generally not interchangeable across ac or dc. A breaker should be used in the service for which it was designed (ac or dc) since changing the usage will change the time delay and trip points.

Circuit breaker ratings are usually based on the ability to carry 115 percent of its rating continuously without tripping, and with the ability to trip within one hour on 138% of rated load. The circuit breaker should be capable of carrying 100% of its rated current at 57° C (135° F) ambient. In addition, the manufacturer's calibration curves for "trip time" vs. percent rated current often depict minimum and maximum trip times at 200% of rated load and at specific ambient temperatures.

Because failure of a circuit breaker to interrupt a fault presents an electrical fire hazard, careful consideration should be given to the class of breaker required based on the available short-circuit current capacity and potential recovery voltages of the electrical system under consideration.

4.5.2.3 Tripping Characteristics

Circuit breakers are available with the following characteristics:

- a. Overcurrent - Instantaneous or inverse time.
- b. Directional overcurrent - instantaneous or inverse time.
- c. Current balance - Instantaneous or inverse time.

- d. Differential current - Instantaneous or inverse time.
("Instantaneous" is defined as less than 0.015 seconds.)

The "trip-free" circuit breaker can be reset against a fault, but will trip automatically as long as the fault exists, even if held in the reset position. Trip-free circuit breakers are generally recommended as giving the maximum amount of protection and safety. The non-trip-free circuit breakers at one time were recommended for critical circuits which had to be maintained at any cost, but current thinking is that all aircraft circuit breakers should be trip free.

4.5.2.4 Thermal Circuit Breakers

Thermal circuit breakers are dependent upon a temperature rise in the sensing element for actuation. Normal operation is achieved by the deflection of a bi-metal thermal element which will open a circuit when a predetermined calibrated temperature is reached. Temperature rise in the sensing element is caused principally from load current I^2R heating. The thermal element will also integrate heating and cooling effects from external sources and will tend to derate or uprate from room temperature calibration with corresponding fluctuations in ambient temperature.

The size of the thermal element, its configuration, and its physical and electrical characteristics will determine the amount of current carrying capacity of the circuit breaker. In some cases, a heater coil is placed next to and electrically in series with the thermal element to augment self heating of the thermal trip element. This is done for ratings below five amperes.

4.5.2.4.1 Thermal, Magnetic Assist

In order to protect wiring, upstream components, and the breaker itself from needless long thermal and mechanical stresses during high fault level currents, an electro-magnet is added to the thermal breaker. This magnetic circuit consists of a few turns of large cross section conductor in series with the thermal element and has little effect on the total breaker impedance. The magnetic assist usually has a cross over point well above the normal overload calibration range; therefore, there is very little effect on the normal thermal response trip time. For high overload conditions, however, the current generates sufficient magnetic force to trip the breaker magnetically without waiting for the bi-metal to deflect. This type of design results in very fast trip times for high overloads that approach near instantaneous tripping times.

4.5.2.4.2 Thermal, Temperature Compensated

A temperature compensated circuit breaker uses a thermal responsive element that compensates for changes in ambient temperature. The compensating element is usually electrically isolated from and independent of the current carrying thermal trip element. The compensator acts only when a change in ambient temperature occurs.

4.5.2.5 Operating Positions

On push-pull manual circuit breakers the position or condition of the circuit breaker is indicated by the push button. A colored band (usually white) will show when the breaker is out and in the "off" or "tripped" position. Pushing the breaker in will restore the breaker to the "on" condition. See Figure 4.5-4.

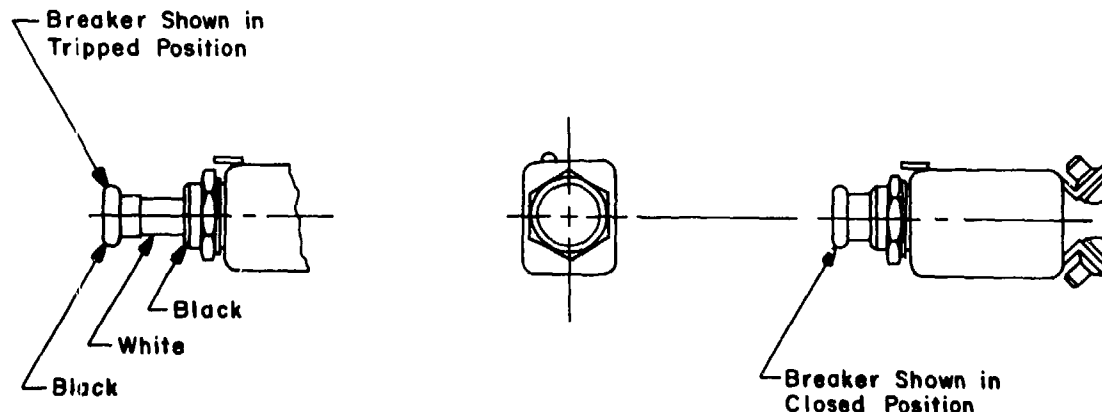


Figure 4.5-4 Push-Pull Manual Circuit Breaker

For trip-free toggle-lever manual circuit breakers the toggle moves to the tripped position when the circuit breaker "trips." To reset the circuit breaker the toggle is moved to the full "open" position and then to the "closed" position at which time the contacts are reset. A tripped toggle-lever can be readily distinguished in a row of circuit breakers, some of which are closed and some of which are "tripped" by the position of the toggle-lever. Figure 4.5-5.

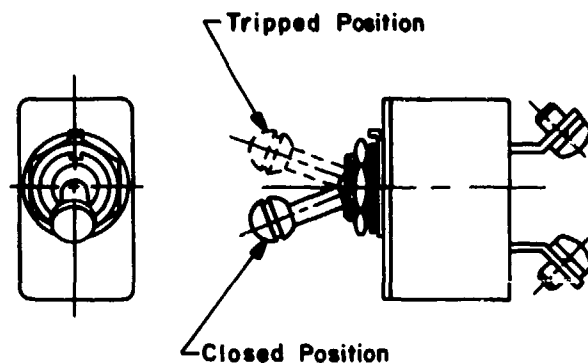


Figure 4.5-5 Toggle-Lever Manual Circuit Breaker

4.5.2.6 Circuit Breaker Coordination

If the circuit in Figure 4.5-6 develops a fault as shown the current increases accordingly (shown parenthetically) it is possible that circuit breaker "A" could trip before circuit breaker "B." This is possible since both breakers are of the same "family" and have highly similar characteristics. Ref. (37).

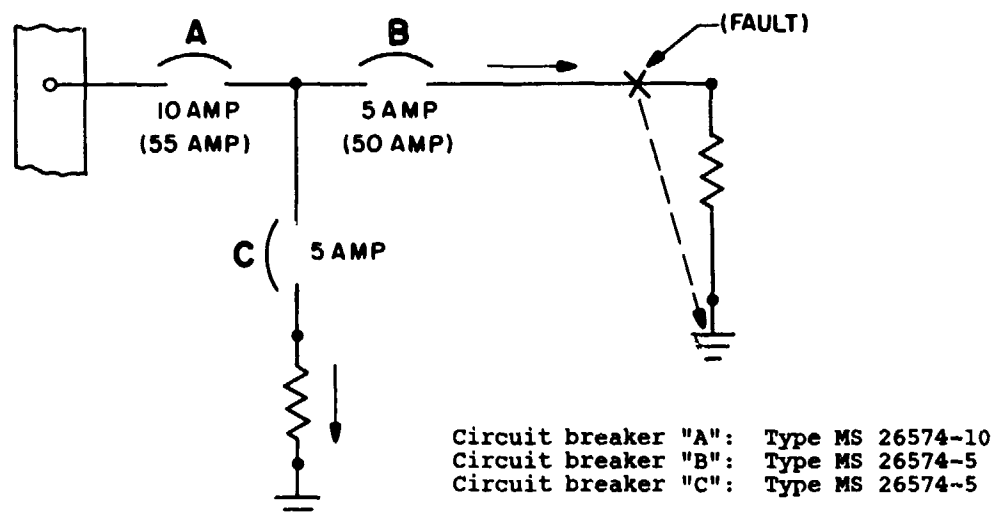


Figure 4.5-6 Circuit Breaker Coordination

Assuming the complete circuit to be at room temperature the following conditions could exist as taken from a vendor's catalog:

Circuit breaker "A": Trip time minimum for a 550% rated load is about 0.1 second.

Circuit breaker "B": Trip time maximum for a 1000% rated load is about 0.3 second.

If circuit breakers are to be used then a different family of circuit breakers can provide adequate coordination. There are several to choose from and one such circuit breaker can provide a minimum time of 0.33 seconds and a maximum time of 1.0 plus seconds at room temperature. This range of time used for circuit breaker "A" would enable circuit breaker "B" to trip first.

The coordination of circuit breakers at different temperatures is determined using this same procedure.

4.5.2.7 Safety Conditions

Manual reclosure of a non-trip-free circuit breaker on a fault is an undesirable situation from a safety standpoint. If a circuit is so critical that it must be maintained even under fault conditions, consideration should be given to the use of parallel circuitry with duplicate circuit breakers.

Adverse ambient temperature conditions should be taken into account in planning circuit breaker installations. The tripping time of thermal circuit breakers is affected by ambient, both at or near rated load and under overload conditions. Use of a thermal circuit breaker permits the maximum utilization of circuits when the temperature-time tripping characteristics of the circuit breaker approximate the temperature-time curve of the cable protected. If a thermal circuit breaker and the cable being protected are in widely different ambients, derating or uprating the circuit breaker should be considered in planning the installation. Toggle-lever circuit breakers have the advantage of ease of operation and can be used conveniently as a combination of switch and circuit breaker. Toggle-lever circuit breakers in critical circuits, however, should be protected by guards to prevent accidental opening or closure by bumping, snagging, falling objects, etc. (See Figure 4.5-5)

Push-pull circuit breakers have the advantage of being less susceptible to accidental opening, and are usually available with greater interrupting capacities. They are, however, difficult to operate with heavy gloves on.

4.5.2.8 Typical Problems

1. Difficulties experienced during qualification testing of circuit breakers are often a result of inadequate test equipment, improper test procedures, unrealistic requirements, or combinations of all three. The test procedure must recognize the design purposes of a circuit breaker.
2. The selected trip limits must be realistic and conform to the required performance data.
3. Problems can develop when wires are attached to the circuit breaker terminals. When the bolts are tightened the seal between the breaker body and the terminal lug may crack. This crack may not affect the strength of the breaker body, but it does violate the environmental seal.
4. The large and heavy three-phase circuit breakers are screw mounted rather than stem mounted. Without adequate solid mounting, the breaker may "trip" during vibration.
5. Circuit breakers of the type which use cams in its mechanism to hold the actuator in the closed position may fail during vibration if the activator push button is not firmly pressed when closing.
6. Push-pull circuit breakers of the type shown in Figure 4.5-4 display a white band when in the tripped position. In low level lighting conditions visual monitoring of the band is difficult.
7. Circuit breakers of either the push-pull or toggle type are particularly susceptible to inadvertent activation or damage. Special precautions should be taken to protect the circuit breakers by providing protective panels or barrier guards.

4.5.3 Limiters

A limiter is a device which responds only to high values of overcurrent and should be carefully applied with this criterion in mind. It is an aircraft fuse specifically designed with a high temperature melting point to protect electric power distribution systems against short circuit currents. It is manufactured to have a closely-controlled curve of melting current versus time. The use of a silver or copper link having a high melting temperature makes it relatively more insensitive to wide ranges of ambient temperature than a normal fuse. Ref (38).

Historically, the term "limiter" is drawn from the use in 60 Hz circuits where the blowing time was less than a quarter-cycle, effectively "limiting" the fault current. Such operation does not occur at 400 Hz and the limiter must not be considered to have limiting action.

4.5.3.1 Limiter Types

There are two basic types of limiters which are used in aircraft electrical power systems.

1. The most widely used limiter is of the knife blade style. Some designs provide visual indication of a blown limiter by a spring activated pin that extends from the limiter body.
2. The other type of limiter is the bolt-on type with an insulating window covering the link for visual inspection.

4.5.3.2 Limiter Ratings

Limiters are rated according to voltage, current and interrupting capability.

Voltage Rating: Knife-blade type limiters carry a 120/208 volt, 400 Hz ac or 125 volt dc voltage rating. Bolt-on type limiters may be applied in circuits up to 41 volts ac or dc. **CAUTION:** Consult manufacturer's specifications of the two presently available types, neither are entirely suitable for 125-volt dc application.

Current Rating: Knife-blade type limiters are designed to carry 200% rated current for five minutes, and open at 240% within five minutes. These limiters have nominal current ratings from 1 to 60 amperes. Bolt-on type limiters have current ratings from 35 to 500 amperes and follow a typical fuse melting curve with specified tolerances.

Maximum Interrupting Ratings: The maximum interrupting ratings for knife-blade type limiters are 6000 amperes at 120 volts ac, 4200 amperes at 208 volts ac, and 6000 amperes at 125 volts dc. Bolt-on type limiters have interrupting ratings of 10,000 amperes at 32 volts ac or dc.

4.5.3.3 Environmental Effects

The temperature ratings extend from -54°C to $+125^{\circ}\text{C}$ (-65°F to $+257^{\circ}\text{F}$) without significant changes in operation. Altitudes up to 21,340 meters (70,000 feet) do not affect the interrupting rating of the limiter. The terminals on aircraft limiters are silver plated to prevent corrosion and the body is designed to withstand extremes such as fungus, salt spray, sand, and dust. Overall these devices are designed to meet established environmental requirements, and these design requirements should be reviewed as part of the hardware selection process.

4.5.3.4 Limiter Selection

Limiters are useful for isolating high-capacity cables whose short circuit current might damage the generating system. Thus, limiters in aircraft are usually applied as back-up protection for circuit breakers and in multiple cable circuits for isolating a faulty cable.

Where the available short-circuit currents exceed the interrupting rating of a circuit breaker, an aircraft limiter may be used to limit the short circuit current to within the breaker's capability. Figure 4.5-7 is a family of curves showing current as a function of opening time for limiters.

High-capacity limiters need not be accessible for replacement in flight. Since limiters are usually physically located at or near the main bus it is not safe to attempt replacement until power is removed from the bus.

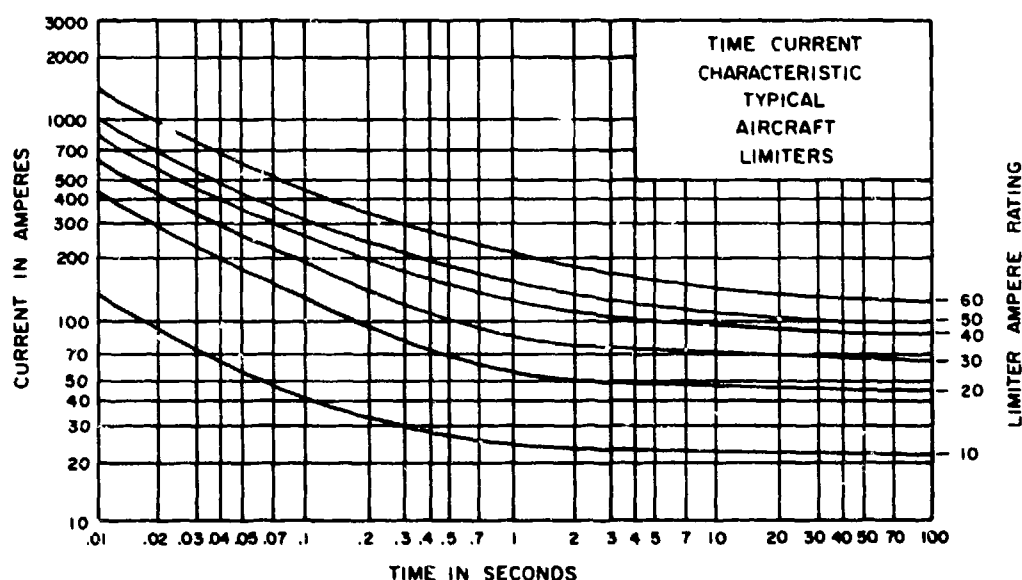


Figure 4.5-7 Time-Current Characteristics of a Typical Aircraft Limiter

4.5.4 Fuse/Limiter Comparison

The difference between fuse and limiter applications may be shown by these two examples: Power leads from the bus to an engine are normally subjected to severe overloading for a short time only. Proper protection of such a cable, still allowing for maximum utilization of a small light cable, can best be achieved by a "slow blow" fuse or other protective devices designed with a current-time characteristic which conforms to that of the cable. In contrast, the power leads from a main bus to a sub-bus usually carry continuous current levels; voltage drop limitations and characteristic loads usually result in conditions in which maximum utilization of the cable is not required. Yet, the main bus and sub-bus must have isolation protection should the sub-bus feeder cable become grounded. This can be done very well by a limiter. Under short circuit conditions the limiter will open and relieve the main bus more quickly than a "slow-blow" fuse.

Limiters should be installed to allow for proper heat dissipation. Particular care should be taken to prevent installing high current rated fuses or limiters in such a way that excessive generated heat does not affect adjacent equipment to which the limiter is attached. Limiters must also be installed in such a way that undue mechanical strain will not be imparted to the limiter link or its case.

4.5.5 Reliability After Inspection

Resettable protective components should not be allowed to develop a history of "tripping". A tripped device may be faulty, may be in a faulty circuit, or may be improperly applied. A tripped circuit should receive immediate postflight analysis.

4.6 The Selection of Wires and Cables

The prime function of a wire is to successfully provide a transmission line for the routing of electrical energy under specified environmental conditions. The selection involves the consideration of the many different aspects of its construction. An understanding of the electrical, mechanical, physical, and chemical capabilities of the materials involved will result in the selection of a wire that will perform in a manner best suited to the system requirements. The proper selection must take into account the conductors, insulation, shielding, jacketing, size, and weight as well as availability and cost. In addition, when specifying signal wiring the wiring twist per unit length must be considered. (Section 3.4.1.1.2).

The majority of the familiar wiring and cable types are standard and/or traceable to Military Specifications, often, by more than one, since a particular named material may be made in many formulations, thus resulting in different characteristics. Refs. (4, 39, 40, 41).

4.6.1 Wire Gages

The American Wire Gage (AWG) series numbers are practically the only gage system now used for wire in the United States. However, a variety of reference books are readily available that relate other gage systems such as the British Standard. Since the AWG concept is based on inches, metric conversions will not be included in the following material.

The basic diameters originally quoted for the AWG spanned from AWG 0000 (0.4600 inch) thru AWG 36 (0.0050 inch). This permitted 40 different wire sizes. The wire sizes were determined by applying the law of geometric progression. (This progression has later been extended to AWG 37 thru AWG 56). Ref. (B8).

The ratio is determined by the following:

$$\frac{I}{a} = b^{n-1} \quad \text{Eq. (4.6-1)}$$

Where

I = the nth term = 0.46000 inch (AWG0000)

a = first term = 0.0050 inch (AWG 36)

b = basic ratio

n = total number of sizes = 40 since there are 40 different sizes.

$$b = \sqrt[39]{\frac{0.4600}{0.0050}} = 1.122932 \quad \text{Eq. (4.6-2)}$$

The following examples will illustrate how the rule is applied to the design of the AWG table.

What is the solid wire diameter of AWG 18?

Use the data provided in Table 4.6-1.

$$I = a(b^{n-1}) \quad \text{Eq. (4.6-3)}$$

Let a = the AWG 36 wire diameter = 0.00500 inch

b = 1.122032 (the basic ratio)

Since a is the first term (or the diameter of AWG 36) then the value of n for AWG 18 is 19 since AWG 18 is the 19th wire gage from the end of the table listing and $n - 1 = 18$.

Thus:

$$I = 0.005 (1.122932^{18})$$

= The diameter of AWG 18

= 0.04030 inch

From Table 4.6-1 of wire gage listings, the diameter of an AWG 18 is 0.0403 inch. Notice that the calculations are only true for a solid wire.

TABLE 4.6-1 Manufacturer's Data Solid and Stranded Wire, AWG 22-16.

Wire size	AWG solid wire		"AWG equivalent" stranded wires		
	Circular mil area	Approximate outer diameter, cm (in.)	Stranding, number of wires X size	Circular mil area	Approximate outer diameter, cm (in.)
22	640	0.0643 (0.0253)	7 X 30 19 X 34* 26 X 36	700 754 650	0.076 (0.030) 0.079 (0.031) 0.076 (0.030)
20	1020	0.0813 (0.0320)	10 X 30 19 X 32* 26 X 34 41 X 36	1000 1216 1032 1025	0.089 (0.035) 0.094 (0.037) 0.091 (0.036) 0.091 (0.036)
18	1620	0.1024 (0.0403)	7 X 26 16 X 30 19 X 30* 41 X 34 65 X 36	1769 1600 1900 1627 1625	0.122 (0.048) 0.119 (0.047) 0.125 (0.049) 0.119 (0.047) 0.119 (0.047)
16	2580	0.1290 (0.0508)	7 X 24 19 X 29* 26 X 30 65 X 34 105 X 36	2828 2426 2600 2580 2625	0.152 (0.060) 0.147 (0.058) 0.150 (0.059) 0.150 (0.059) 0.150 (0.059)

*AN size referred to in MIL-W-5088.

As taken from a Table of Standards and Values the circular mil areas of AWG 36 and AWG 18 are:

AWG 36 = 25 CM

AWG 18 = 1620 CM

The circular mil area of AWG 18 is approximately 64 times that of AWG 36. The weight is approximately 64 times that of the AWG 36 and the resistance is about 1/64th. Using the example above the following general rule can be applied:

An increase of 3 gage numbers doubles the resistance.
halves the cross-sectional area.
halves the weight.

An increase of 6 gage numbers multiplies the resistance by 4.
divides the cross sectional area by 4.
divides the weight by 4.

An increase of 9 gage numbers multiplies the resistance by 8.
divides the cross-sectional area by 8.
divides the weight by 8.

A decrease of 3, 6, or 9 gage numbers has the opposite effect.

It is important to note again that AWG numbers are true AWG for single solid wires only. Because of the complications introduced by the use of stranded wire, it is the practice for some wire manufacturers to omit the gage type and use only wire size as determined by the circular mil area.

The criteria for calling a stranded wire by a particular gage number is based on the circular mils being somewhat the same as that of a solid wire, since they both have nearly similar electrical characteristics. However, notice the diameters. The diameter of a stranded wire, with nearly the same total circular mils, will be different in diameter from the AWG solid wire. Compare the diameter values listed in Table 4.6-1.

4.6.2 Circular Mils (CM):

The cross sectional area of a single conductor determines its resistance and current-carrying capacity. Since most wiring is circular in cross section, it is the practice to use a unit of area which is itself circular. This eliminates the factor π , in the calculation of cross sectional area.

A circular mil (CM) is a unit of area equal to the area of a circle whose diameter is 0.001 inch or one mil.

$$\text{Area in Circular Mils} = \left(\frac{\text{Diameter in inches}}{0.001} \right)^2 \quad \text{Eq. (4.6-4)}$$

For example, referring to Table 4.6-1 the approximate outer diameter of an AWG size 22 wire is .0253 inches.

$$\text{Circular Mils (CM)} = \left(\frac{0.0253}{0.001} \right)^2 = 640 \text{ CM} \quad \text{Eq. (4.6-5)}$$

4.6.3 The AN Wire Gage Size

The use of circular mil area as a criterion for selecting wire gage size can be illustrated by referring to Table 4.6-1. Notice the variations in circular mil area and the outer diameters of each wire. These variations may not only affect the proper selection of wire termination hardware but may also affect the maximum designed current flow; the one exception, however, is the AN type wiring designated by the asterisk. The AN type wiring (gage size) is MIL specified and current ratings and termination hardware are addressed in MIL-W-5088. (See Section 4.6.5).

4.6.4 Wire Construction

Quite often airframe wiring is thought of as only a means of conveying electrical energy from one point to another. As a direct result many instrumentation engineers overlook some of the design considerations inherent in the construction of airframe wiring.

4.6.4.1 Solid Wire Conductors

Solid wire conductors are generally the least expensive, but they are physically quite rigid. Solid wires cannot withstand flexing, and wires smaller than AWG 22 may change their molecular crystalline characteristics during vibration, and fail. In general, for aircraft uses, solid wiring should be limited to very short lengths and held rigidly in place. Further, it is recommended that coaxial cables be used with stranded center conductors rather than solid conductors. The use of solid conductor wire wrapped terminals should be limited to wiring internal to equipments properly installed to withstand shock and vibration forces.

4.6.4.2 Stranded Wire Construction

Stranded wire conductors were developed for the practical considerations of greater flexibility and flex life. A stranded wire can withstand vibration much better than a solid wire. Further, any surface damage such as nicking or cutting when the insulation is stripped off, can have less mechanical significance on a stranded wire than a solid wire.

Stranded wiring is more expensive than equivalent solid wires and its weight and resistance is slightly greater. It should be remembered that the flexibility of a finished insulated wire is affected not only by the conductor strands but also by the insulation type and thickness.

4.6.4.2.1 Lay or Pitch

The lay of a helically laid wire is the unit axial length for one full turn of the helix. Similar wire sizes are often commercially available in different lay lengths, although just about any length can be made. The shorter the lay, the greater the flexibility and strands would be less likely to untwist or flare out when stripped bare. But shorter lays are more costly, elongation is

reduced and the extra working of the lay could make the copper more brittle. The direction of the lay length is important with some insulation stripping machines. Left and right helical lays are shown in Figure 4.6-1.

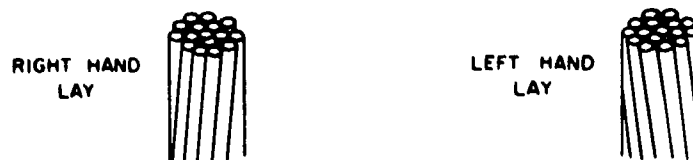


Figure 4.6-1 Examples of Right and Left Hand Lay.

4.6.4.2.2 Stranding Combinations

There are several types of stranding combinations available. Some are stronger, and more flexible; others are cheaper. Generally, all of the individual strands of wire are of the same size; that is, each strand is the same circular mil area.

4.6.4.2.3 Concentric Stranding

Concentric stranding consists of a central wire surrounded by one or more helically laid layers. Concentric stranding gives an almost perfect circular cross section, which permits the best centering of a wire within its covering. This allows the application of a uniform thickness of insulation.

The mathematics of circles and diameters shows that 6 wires fit quite nicely around one wire, and each succeeding layer fits neatly if it is increased by six more wires. This results in "natural" groupings of 7, 19, 37, 61, 91, 127, and so on, stranded wires (see Figure 4.6-2(a)).

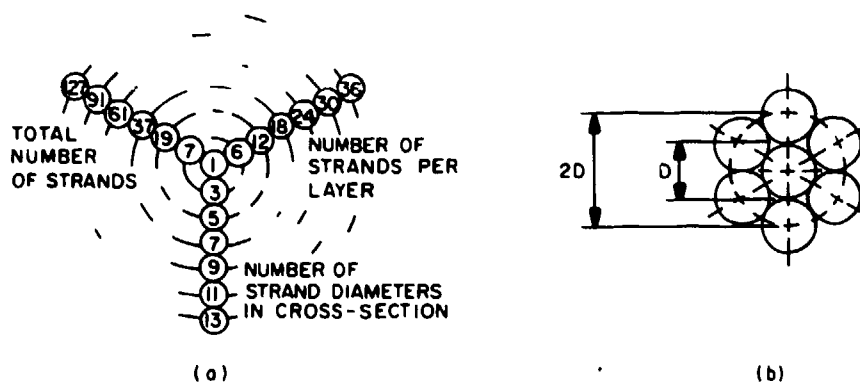


Figure 4.6-2 Geometry of a Concentric Stranded Wire

By far the most popular stranding is the true concentric. Alternate layers of stranding are applied in left and right hand lays. The bare outside diameter of this type of stranding is quite predictable as 3, 5, 7, 9, etc., times the diameter D of one strand as shown in Figure 4.6-2(b).

4.6.4.2.4 Uni-Directional Stranding

In this design, each succeeding layer of wires is laid in the same direction. The final result is almost circular and its bare diameter is not accurately predictable. However, uni-directional construction is more flexible than true concentric and has a longer flex life. It is also less expensive than true concentric since the manufacturing process can lay more than one layer of wire at a time.

4.6.4.2.5 Bunched Stranding

This stranding method twists the wires together without a pre-determined pattern. This is the least expensive way to strand wires, but the end result is more of a hexagon in shape with no real uniformity. The peripheral shape can be made more circular, with added cost, by an additional drawing operation thru a die that re-forms the strands. Examples of bunched stranding are shown in Figure 4.6-3.

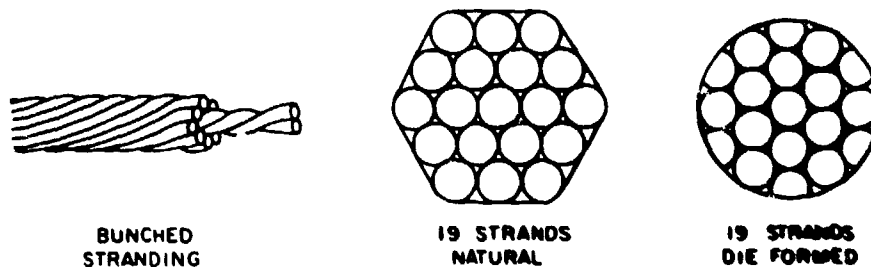


Figure 4.6-3 Examples of Bunched Stranding.

4.6.4.2.6 Stranded Wire: Problems

During the era of soldered contacts on connectors and terminals, the peripheral geometry of a single wire was somewhat incidental as shown by the various soldered terminals in Figure 4.6-4.

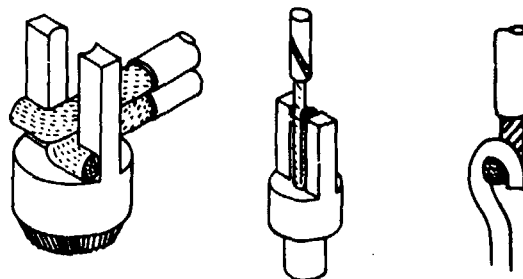


Figure 4.6-4 Soldered Terminal and Connector Contacts.

The advent of the crimp contact, however, required that a round wire be inserted into a cylindrical barrel. Since each contact is made for more than one wire size, the largest wire size must be round so as to fit into the barrel quickly without disturbing the strands.

One further comment regarding a round stranded wire relates to wire strippers. Wire strippers are designed to strip round wires, and non-rounded variations can result in wire damage to individual wire strands. A loss of one or more wire strands will limit the wire current capacity.

4.6.4.3 Conductor Materials

Usually the system installation requirements determine the characteristics of the wire conductor with economics and availability helping make the choice. Conductor materials are selected for their physical as well as electrical characteristics. The conductor must have high tensile strength and elongation, good workability, flexibility and flex life, acceptable conductivity and resistivity, low brittleness and high resistance to corrosion. Copper is by far the best choice in metals. Taking into account all of its qualities, copper has the best combination of electrical and thermal properties, malleability, strength, and the ability to be coated or alloyed for special applications. This is not to discount, however, other good metals and alloys that can be used for special purposes or as they become economically practical.

4.6.4.3.1 Electrolytic Tough Pitch (ETP) Copper

This metal is the the most commonly used for electrical conductors. ETP copper is refined to a high degree of purity, the main impurity being a small amount of copper oxide which could cause embrittlement at high temperatures. Some examples of the types and conductivity are: (as related to pure copper)

- A. Soft copper - About 99.9% conductivity.
- B. Medium Drawn copper - about 97% conductivity.

C. Hard-drawn copper - about 97% conductivity.

There are other ETP coppers, but they are not commonly used for wiring conductors.

4.6.4.3.2 Oxygen Free High Conductivity (OFHC) Copper

OFHC copper is refined by a special process to a very pure grade of copper with practically 100% conductivity. The improvement in conductivity over ETP copper is of minor importance, but the OFHC copper has more ductility which adds appreciably to the mechanical capabilities of the copper.

4.6.4.3.3 Copper Alloys

The trend towards miniaturization and high strength conductors has led to the development of various copper alloys with exceptional mechanical capabilities. These types can have from 200% to 500% more tensile strength than that of copper alone and also have better flex life. Due to different manufacturing methods and results, it is always best to specify the desired performance of the alloy rather than just calling out the specific alloy. Although dozens of alloys are commercially available, only those which are generally used will be described.

4.6.4.3.3.1 Cadmium-Chromium-Copper Alloy

Cadmium-Chromium-copper alloy, Alloy 135, exhibits quite consistent and good physical characteristics with approximately 85% conductivity. Of the copper alloys, this type has about the best tensile strength and flex life. Its high tensile strength and low elongation makes this wire especially suitable for use in wirewrap applications requiring small wires.

4.6.4.3.3.2 Cadmium-Copper Alloy

Cadmium-copper alloy, Alloy 80 or 85 types, is a high-strength alloy used in fine wire applications. This alloy has approximately 85% conductivity, is easy to work with and is relatively inexpensive. However, this alloy has a softening temperature of approximately 175° C (347° F).

4.6.4.3.3.3 Zirconium-Copper Alloy

Zirconium-copper alloy, of the Alloy 63 type, has good physical characteristics and can be used up to 400° C (752° F) without trouble.

4.6.4.3.3.4 Copper-Covered Steel Wire (Also called COPPERWELD)

Copperweld is not an alloy in the true sense of the word. It is made by fusing an outer shell of copper onto a central steel core. This combines the excellent properties of copper with the high strength of steel. The normal conductivity is 30 or 40%, but where the application requires the transfer of radio frequency energy, the conductivity approaches 100% due to 'skin-effect'. Copperweld has much better flex life and twice the strength of copper alone.

4.6.4.3.4 Wire Coatings

Copper has an inherent tendency to oxidize. At room temperature, bare copper will slowly combine with the oxygen in the air to form a surface coating of black copper-oxide which gets thicker with time. Raising the temperature will accelerate the process. This oxide coating transforms copper into a very poor conductor. Various coatings are used to retard this oxidizing process.

4.6.4.3.4.1 Tin Coating

Tin coatings are the most commonly used. In addition to being an inexpensive way to protect the copper from oxidation, tinning the wire aids in its solderability. Coating the wires with tin adds to its cost, but this price increase more than offsets the copper oxidation preventative capabilities. Tinning, does, however, slightly increase the basic resistance of the wire.

4.6.4.3.4.2 Heavy Tin Coating

Heavy tin coated wires are the same as normally tin coated wires, except that the individual strands are coated 3 to 4 times as thick. Used with high-frequency induction heaters the tin is melted in the stripped area only, bonding the strands together for much easier soldering. This together for much easier soldering. This wire is heavier and stiffer than normally tinned wire and costs approximately 10% more, but this is made up for by its easier soldering by machine.

4.6.4.3.4.3 Pre-Fused Tin Coating

For pre-fused tin coating, the individual strands are heavy tin coated, then fused all along the length of the wire prior to becoming insulation covered. The strands remain bonded together when stripped anywhere along the

length. This makes for very easy soldering, but the wire is much more rigid than normally coated wires and its flex life is reduced.

4.6.4.3.4.4 Tin Over-Coating

For tin over-coating, the individual strands are normally tin coated, then the whole stranded wire is given an extra tin coating. This extra tin coating bonds together the outer perimeter of the strands. The strands remain bonded together when stripped anywhere along the length. This makes for very easy soldering. This wire is more rigid than normally tinned wire, but the bonding is easily broken under flexure.

4.6.4.3.4.5 Tin Top-Coating

For tin top-coating, the individual strands are bare; then the whole stranded wire is given a tin coating. Tin top-coated wire has the same properties as tin over-coated wire; it is less expensive although it is also less corrosion resistant.

4.6.4.3.4.6 Silver Coating

Silver coating is a highly desirable coating with excellent electrical properties. Silver coated wires have high conductivity, good solderability, excellent oxidant resistance, and is good for use up to 200° C (392° F). At radio frequencies, the losses of silver coated wire are very low. Silver coated wire costs more than tin coated wire, and its potential for wicking is considered a disadvantage.

4.6.4.3.4.7 Nickel Coating

Nickel coating is a highly desirable coating with excellent electrical properties. Nickel coated wire has excellent oxidation resistance and is good for use up to 300° C (512° F). The solderability of nickel coated wire is easy enough with the use of corrosive fluxes. Nickel coated wire is comparatively costly, and because of its hardness, it is not recommended for use with crimp terminals.

4.6.4.3.5 Aluminum Conductors

Aluminum conductors have been used for years in the electrical power industry, and large sizes have been used in aircraft. In general, the aluminum conductors used to date have been 8-gage or larger. These wires were practically pure aluminum and had very poor mechanical characteristics. Experiments performed with wires smaller than 8-gage and of the same nearly pure aluminum content degraded rapidly during handling.

One very bothersome problem was the removal of the oxide coating that immediately forms on the conductor when it is exposed to air. For example, copper conductors in a stranded wire are plated to insure a guaranteed transverse conductance (conductivity between wire strands). Initially the stranded aluminum wires were not similarly plated and good transverse conductance was never achieved. Today, however, the conductors are plated and good transverse conductance is normal.

Regardless of the many problems encountered with aluminum electrical conductors its advantages relative to weight alone make it especially desirable in aerospace applications. Size-for-size shielded aluminum wires can provide up to a 66 percent reduction in weight when compared to copper.

4.6.4.3.6 Copper-Aluminum Systems

As aluminum wire technology advances, the acceptance of aluminum wiring will probably be slow. The logical manner of progression is a mixed system of copper and aluminum. To date, however, the effort to use existing copper terminations have been less than successful. The copper alloys are particularly active in producing electrolytic corrosion when exposed to an aluminum alloy. Platings can be used for mutual protection, but the cut ends of the aluminum wire strand expose its core. The exposed core adjacent to any exposed copper alloy only needs moisture to start corroding the aluminum.

4.6.4.4 Insulation and Jacket Materials

There is no perfect, all around insulation material. Accordingly, there are a great many insulation and jacketing materials available, each with its own application. The selection then of the best material becomes a compromise between what is needed for the system installation and of what is available.

Selection of an insulation material should be based on the intended use under various conditions requiring knowledge of the electrical, environmental, chemical, physical, and mechanical factors. Other factors governing selection include material compatibility with encapsulation, potting compounds, conformal coatings, adhesives, shrinkable tubing, marking capabilities, and toxicity.

4.6.4.4.1 Voltage Rating

The voltage rating as given by the manufacturer is the safe operating maximum voltage that may be continuously applied to a finished wire. This value represents a safety value that takes into account all of the normally expressed electrical stresses. For a given insulator type the wall thickness is directly proportional to its voltage rating.

It is a mistake to assume that a wire with a higher voltage rating is a better wire since there is nothing to gain by using a wire with a higher voltage rating than required. The penalties are added cost, size, and weight.

4.6.4.4.2 Environmental Characteristics

Sustaining the operating characteristics of a material is usually dependent upon the ability of the material to resist the harmful effects of its environment.

4.6.4.4.2.1 Temperature

This is the operating temperature range over which the insulated wire is expected to operate continuously without any loss of its basic properties. This includes the ambient temperature plus the increase in temperature due to current flow. (See Section 4.6.5.)

4.6.4.4.2.2 Porosity of Insulation (Moisture)

Moisture resistance is the ability of a material to resist the absorption of moisture during conditions of humidity. The presence of moisture in a material greatly reduces the insulation electrical capabilities.

4.6.4.4.2.3 Aging

Combinations of extreme environmental conditions will contribute to the deterioration of the wire insulation over prolonged periods of time.

4.6.4.4.2.4 Ozone Resistance

Ozone resistance is the ability of a material to withstand a high concentration of oxygen (ozone) produced by the discharge of electricity in the air. The external energy field around a wire, if sufficiently intense in air, will generate surface discharge and convert atmospheric oxygen into ozone which may be destructive to the insulation.

4.6.4.4.2.5 Oxidation Resistance

Oxidation resistance is the ability of a material to withstand the surface degradation caused by the normal oxygen in the air.

4.6.4.4.2.6 Radiation Resistance

Radiation resistance is the ability of a material to withstand exposure to nuclear radiation and is expressed in rads-gamma. Degradation will occur more readily when the insulation is operated at its rated high temperature, or when outgassed material is present.

4.6.4.4.2.7 Resistance to Chemicals, Fluids, and Gases

An insulation material will vary in its ability to withstand contact with any chemical, fluid, or gas. Of the many possible acids, oils, alkalines, solvents, gases, or other corrosive and contaminating elements, a material can withstand some with ease, yet break down rapidly when exposed to others. Hence, each material must be investigated separately in accordance with the expected system atmosphere.

4.6.4.4.3 Mechanical and Physical Characteristics

Sustaining the operating characteristics of a material is also dependent upon the ability of a material to stand up under physical abuse or movement required by handling and use in a system.

4.6.4.4.3.1 Abrasion Resistance

Abrasion resistance is the ability of a material to resist surface wear or other abrasive conditions. This is the most common and abusive condition that a wire is subjected to.

4.6.4.4.3.2 Cut-Through Resistance

Cut-through resistance is the ability of a material to resist penetration by a pointed or knife-like edge. This is important in tightly wrapped or wirewrap systems where the wire may be pressed against a sharp corner.

4.6.4.4.3.3 Flammability (also called Flame Resistance)

Flammable: The material will burn, even after the flame source has been removed.

Self-Extinguishing: The material may burn, but will extinguish itself once the flame source has been removed.

Non-Flammable: The material will not burn under any condition, although it may char a little.

4.6.4.4.3.4 Cold Flow Resistance:

Cold flow resistance is the ability of a material to withstand a physical pressure from an outside force for long periods without any permanent deformation. This resistance also augments cut-through resistance.

4.6.4.4.3.5 Flexibility

Flexibility is the ability of a material to be bent sharply and repeatedly without damage. Very important in wire handling.

4.6.4.4.3.6 Flex Life

Flex life is a measure of the ability of a material to withstand a specified number of sharp bends without damage. This is important in systems that require repeated equipment changes.

4.6.4.4.3.7 Adhesion of Insulation to the Conductor:

The adhesion of the insulation to the conductor is a measure of the ability of a material to remain bonded to the conductor during wire preparation. Important when handling lengths of 30 centimeters (12 inches) or less.

4.6.4.4.3.8 Elongation

Elongation is the percent increase in length that a material can be stretched before there is any sign of rupture or break; this characteristic is very important in system harness fabrication.

4.6.4.4.3.9 Tensile Strength

Tensile strength is the basic strength factor of a material. It is the ability of a material to withstand the specified tension without damage, such as breaking, cracking, or tearing. After aging, the tensile strength is decreased.

4.6.4.4.3.10 Outgassing

Outgassing is the evaporation or sublimation of materials because of exposure to the vacuum conditions of space. In space, outgassing will degrade any insulation, especially those that contain plasticizers, flame retardants, or other modifiers. In such materials, even a slight change can nullify the additive properties of the modifiers. Outgassing degrades the radiation resistance properties of an insulation.

4.6.4.5 Insulation Material Types

Listed in Table 4.6-2 are some of the typical insulation materials and their characteristics as judged from routine experience.

Table 4.6-2 Comparative Environmental and Mechanical Characteristics of Some Typical Insulation Materials

Insulation Material	Resistance to -							
	Moisture	Abrasion	Cut-through	Flam-mability	Chemical	Weather	Ozone	Oxidation
PVC	good	fair	poor	self ext.	good	good	good	exc.
PTFE	exc	fair	fair	non-flam.	exc.	exc.	exc.	exc.
FEP	exc	fair	fair	non-flam.	exc.	exc.	exc.	exc.
Polyalkene	good	good	good	self ext.	good	exc.	good.	exc.
Kynar	good	exc.	exc.	self ext	good	exc.	good	---
Kapton	exc	exc	exc	non-flam	exc.	exc.	exc.	exc.
Nylon	poor	good	good	self ext.	good	good	good	exc.
Mylar	good	exc.	exc.	flammable	good	---	---	---
Polyethylene	exc.	poor	poor	flammable	good	good	exc.	exc.
Silicone	poor	fair	poor	flammable	fair	exc.	exc.	exc.
Neoprene	good	exc.	good	self ext.	good	good	good	exc.
Butyl	good	fair	fair	flammable	good	exc.	good	exc.
Kel-F	good	good	good	non-flam	good	good	good	---
Polypropylene	good	good	good	self-ext	good	exc	good	exc

4.6.4.5.1 Polytetrafluoroethylene - PTFE - TFE (DuPont: Teflon)

PTFE is a popular and versatile fluorocarbon insulation material. PTFE has excellent electrical, thermal, and chemical properties. It is excellent for use in high frequency applications, and its high heat resistance aids in soldering operations. PTFE is rated at +200° C (392° F) with silver-coated conductors, raised to +260° C (500° F) with nickel-coated conductors. PTFE is expensive, but this disadvantage is offset by its ease in handling and its higher current-carrying capabilities, which makes it possible to operate with more current in smaller wires. PTFE is also good for use in space environments. The use of PTFE is limited by its poor abrasion and cold-flow resistance and its poor adhesion to conductors which makes it too slippery to handle in short lengths of 30 centimeters (12 inches) or less. PTFE has relatively poor marking characteristics, since in time, blue turns to gray and red turns to orange, although some of the newer additives improve these properties. PTFE is sometimes doubled with other materials, where each material improves the lesser properties of the other.

4.6.4.5.2 Fluorinated Ethylene Propylene - FEP (Dupont:Teflon 100)

FEP has almost the same advantages in use as PTFE with its excellent electrical, thermal, and chemical properties. The differences, though small, are important. FEP is rated at +200° C (392° F), 50° C (122° F) lower than PTFE. Hence its heat resistance and soldering capabilities are just a little poorer than PTFE. But FEP is less costly than PTFE because the manufacturing techniques are simpler. FEP is easier to color-code. FEP is sometimes doubled with other materials, where each material improves the lesser properties of the other. A new type, foamed FEP, is getting some usage, since it has a low dielectric constant and is even better electrically than PTFE.

4.6.4.5.3 Cross-Linked Polyalkene - Under an Over-Jacket of Cross-Linked Kynar:

Cross-linked polyalkene under an over-jacket of crosslinked Kynar is one of the better combinations of insulation materials. This combination is lighter than PTFE, but the biggest advantage of a cross-linked material is its excellent radiation resistance, which allows it to operate in space environments. This combination exhibits good electrical and excellent mechanical properties, since each material improves the lesser properties of the other. Cross-linked alkene is also formulated with a cross-linked imide material, which further improves the mechanical properties of the primary insulation. This formulation is then covered by a very tough imide over-jacket which also has excellent radiation resistance.

4.6.4.5.4 Polyimide (DuPont: Kapton)

Kapton is one of the better insulation materials. It is a very tough material with excellent mechanical, thermal and chemical properties. Its radiation resistance is outstanding. Kapton in very thin-wall construction is used in combination with other insulation materials, where each material improves the lesser properties of the other. Kapton is not easy to work with because it is stiff and difficult to strip. Ref. (42)

4.6.4.5.5 Nylon

Nylon, a member of the polyamide family, is a very tough insulation material. Because of its toughness, it is used extensively as an over-jacket. The use of Nylon is limited by its relatively poor electrical properties and its poor moisture resistance. The nature of Nylon limits its use to wires under 0.635 centimeters (0.250 inch) in diameter.

4.6.4.5.6 Polyethylene Terephthalate (DuPont: Mylar)

Mylar is a tough insulation material with a good balance of electrical and mechanical properties. In very thin-wall constructions, Mylar is used as an over-jacket to prevent migration through shielding braid. Often, Mylar is formulated with copper or aluminum to form a shielding braid that is laid over a shielding braid already present to improve the shielding efficiency. The use of Mylar is limited by its flammability.

4.6.4.5.7 Polyvinylchloride (PVC)

Polyvinylchloride (PVC) is the most popular and versatile low-cost insulation material for operation at temperatures to 150° C (302° F). PVC has acceptable electric properties at power and audio frequencies. PVC is soft, flexible material. At additional cost, copolymers with additives are made that improve the electrical and mechanical properties of PVC. The use of PVC is limited by its poor cut-through resistance. In addition, at low temperatures PVC insulation stiffens and may crack when bent. PVC insulation is also susceptible to solder iron damage during the assembly stages. To some extent, crimped contacts alleviate this problem.

4.6.4.5.8 Polyvinylidene Fluoride - (Pennsalt: Kynar)

Kynar is a very tough insulation material with excellent cold flow and abrasion resistance. The use of Kynar is limited by its high capacitance losses due to its relatively high dielectric constant. Kynar is usually used as an over-jacket over another insulation material, where each material improves the lesser properties of the other. Kynar can be used as a replacement for Nylon. It is not quite as tough as Nylon, but it has much better moisture resistance.

4.6.4.5.9 Polyethylene

Polyethylene, a member of the polyolefin family, has excellent electrical properties, but poor mechanical and thermal properties. Polyethylene is very light in weight and performs very well in high frequency applications due to its low capacitance losses. The use of polyethylene is limited by its flammability, its poor abrasion and cut-through resistance, its low heat resistance and its stiffness, although some of the new additives improve these properties. Polyethylene is usually used under an over-jacket of a tougher material. Cellular or foamed polyethylene has better electrical properties than solid polyethylene, but they are not as durable.

4.6.4.5.10 Silicone Rubber

Silicone in all of its many formulations is used mostly in high voltage applications. This material has good electrical and thermal properties and better radiation resistance than most other thermoplastics. The use of silicone is limited primarily by its flammability, although during burning it develops a white, non-conductive ash which temporarily forms an added good insulation. Silicone is also limited by its poor mechanical properties and its poor moisture and chemical resistance.

4.6.4.5.11 Polychloroprene - Neoprene

Neoprene is a tough insulation material and for this reason is usually used as an over-jacket. Neoprene is excellent for use at power and audio frequencies, and at low voltages. The use of Neoprene is limited by its poor thermal properties, and its high capacitance losses due to the high dielectric constant.

4.6.4.5.12 Butyl Rubber

Butyl is somewhat similar to Neoprene. Though not as tough as Neoprene, Butyl has good electrical properties. Butyl is a flexible material and is compatible with the more exotic fuels.

4.6.4.5.13 Monochlorotrifluoroethylene (3M: Kel-F)

Kel-F has almost as good properties as PTFE. It is tougher than PTFE, but doesn't operate as well at the higher temperatures. It is not as popular as PTFE since the cost is about the same, but its versatility is not as good as PTFE.

4.6.4.5.14 Polypropylene

Polypropylene, a member of the polyolefin family, has good electrical and mechanical properties. It is a tough material, as good as Nylon, which makes it practical for use as an over-jacket. The use of polypropylene is limited by its poor operating characteristics at moderately low temperatures. Polypropylene has poor marking characteristics, since in time, blue turns to gray and red turns to orange. Presently, the main area of use for Polypropylene is in telephone communications cable.

4.6.4.6 Shielding

Important circuit advantages are gained by the addition of a metal shield around an insulated wire. The purpose of the shielding is (1) to prevent external electrical energy fields from entering the internal conductor and interfering with the circuit signal, (2) to restrict the electric field generated by the inner conductor from radiating into adjacent or nearby conductors, or (3) to act as a secondary conductor in matched or tuned circuits. Basically, shielding prevents noise, cross-talk, RF leakage currents, and shock to personnel, since in any high intensity power area, such as radar, ac power circuits, motors, multi-conductor cables, etc., any conductor can act as the secondary winding of a transformer and pick up these external energy sources.

Like other elements of a wire, there is no perfect construction method for shielding. There are compromises between the amount of electrical energy shielding that can be obtained, the flexibility lost, and the additional size, weight, and cost. Twisted pairs is the easiest and best protection method for two wires to cancel the electromagnetic effect between two wires. This is most effective for a balanced pair, at low frequencies. But for general use shielding, an insulated conductive metal covering is the best method.

4.6.4.6.1 Braided Round Wire Shielding

By far the most common and most effective shielding is braided round copper wires suitably coated to prevent corrosion and oxidation. This method gives reasonable flexibility and flex life, with good coverage from 80% to 98% depending upon how closely it is braided. Termination methods, while not simple, are well known. This method adds the most in size and weight but is the least expensive, since it is the easiest method to manufacture. These shields should not be placed directly over thermoplastic insulation materials since heating the shield during soldering, for example, could cause the insulation to "flow" and permit the shield to come in contact with the inner conductor.

4.6.4.6.2 Braided Flat Wire Shielding

Braided flat wire shielding is widely used. It is made the same way as round wire shielding except that the individual strands are flat. The build-up is much smaller and lighter, but termination is difficult, requiring special techniques. Braided flat wire is limited by its poor flex life (approx. 10-15 flexes). Braided flat wire should not be laid in tight bends, since the bends can cause the flat wires to kink and break, resulting in a loss of shielding effectiveness. Clamping the shielding near any point of flexing or bending will also cause the strands to break.

4.6.4.7 Jackets - Over-Jackets - Secondary Insulation Materials

Jacket insulation materials are often laid as an over-jacket over a primary insulation to give added protection to the construction. The best jacket materials are those that can be used in thin-wall construction that gives to the finished wire or cable the mechanical, environmental, and chemical properties that the unfinished wire lacks. Secondary insulation materials selected should always be temperature matched and compatible with the primary insulation, since migration between materials occurs which could contaminate the insulations.

Jackets are almost always laid over a shielding braid to insulate the shield from ground, other shields, or personnel.

Jackets are also used as a binder over groups of wires or cables to make a multi-conductor cable.

In addition to materials normally used as insulations, jackets can be made of fibrous or textile braids, suitably treated to give protection to the wire or cable.

4.6.4.8 Multi-Conductor Cables

Increasingly complex circuitry makes the use of many wires within a single jacket a practical solution. A multi-conductor cable is simply a group of individual wires covered by an overall jacket to hold the wires together in a bundle or harness. There is no end to the types and combinations of wires that can be and are made into multi-conductor cable constructions. The properties of multi-conductor cable are cumulatively those of the individual conductors and the insulation materials.

In multi-conductor cables, the wires can be laid concentrically, bunched or parallel, as desired. Shielding can be placed over individual wires or groups of wires or over all the wires under the jacket, in any of the acceptable shielding braid constructions. Fillers or binders are often used to give a roundness to the finished cable.

Individual jackets and overall jackets should be compatible with each other in their electrical and environmental properties and, if desired, they should be capable of sliding against each other, enabling free movement during bending.

Sometimes a multi-conductor cable without an overall jacket is desired. This harness is simply spot-tied together at proper intervals.

The current carrying capacity of multi-conductor cables is much lower than those of individual wires due to the greatly decreased surface area of a wire exposed to the atmosphere. Each multi-conductor cable must be investigated for this reduced capacity (See Section 4.6.5).

4.6.4.9 Color Coding

Color coding of wires is simply a system for easy identification by personnel. Color coding is done by solid colors, colored tracer strips or bands over a solid color background, colored braids or surface printing.

Color coding generally follows the requirements of MIL-STD-681, which are universally known and accepted. This specification allows the use of 10 basic colors and assigns a number to each color (see Table 4.6-4). Ref. (43).

Table 4.6-3 MIL-STD-681 Color Code

Number	Color	Number	Color
0	Black	5	Green
1	Brown	6	Blue
2	Red	7	Violet
3	Orange	8	Gray
4	Yellow	9	White

MIL-STD-681 allows for the use of only these 10 basic colors with up to three color stripes on a white background. More than three stripes has been found to be impractical.

For easy identification when there is more than one stripe, the first stripe is much wider than the others, which are read in sequence. Using the NUMBER-COLOR system, a wire can easily be identified. For example 9346 is a wire with a 9-White background (always white), followed by a 3-Orange stripe (wide), followed by a 4-yellow stripe (narrow), followed by a 6-Blue stripe (narrow).

MIL-STD-681 also gives functional relationships to certain colors or color combinations which saves a great deal of time for personnel to identify certain functions generally associated with circuitry.

For color retention black is the preferred color for radiation resistance applications. With PTFE or polypropylene insulation, blue and red should be avoided, since in time blue will turn to gray and red will turn to orange. The use of heat guns should be avoided as black colored insulation absorbs heat quicker than the lighter colors.

4.6.5 Wire Gage Selection

The actual selection of the wiring that is installed in aerospace vehicles is carefully guided by suitable specifications that have been developed over the years. Once such specification is MIL-W-5088H. (Ref. 4).

4.6.5.1 History of MIL-W-5088H dated 20 July 1979

This specification was initially published in March 1951, superseding the AN-W-14a specification dated May 1945. Then as now, the specification outlines the selection and installation of wiring and wiring devices used in aerospace vehicles. The intent was to establish a design-selection criteria for basic aerospace vehicle wiring. Fortunately, over the thirty years since its inception, sufficient supporting data has been added to this specification to provide guidance for instrumentation subsystem installations.

Two basic types of information are required for the selection of a wire size. The first is the data that defines the current carrying capacity of a single wire in free air at sea level ambient temperatures. The second is environmental operating information relative to using the wire as part of a wire bundle at altitudes other than sea level.

The importance of the type of data contained in MIL-W-5088H cannot be overemphasized. The instrumentation engineer can use this data to optimize the selection of wire size and current carrying capacities or use it to evaluate wiring already installed in the aircraft.

The installation of instrumentation wiring requires a thorough knowledge of the subsystem to be tested, the test procedures to be used, and the mission profile. For example, evaluation of a landing-aid subsystem may require that the instrumentation system be operational only for altitudes below 3 kilometers

(10,000 feet). If so, then selections of cable size and current capacity are not critical factors. At increasingly higher altitudes, however, altitude becomes a critical selection factor and must be considered.

4.6.5.2 Using MIL-W-5088H Selection Criteria

To illustrate the use of MIL-W-5088H, Figures 3, 4, and 5 (From MIL-W-5088H) have been re-printed in this section as Figures 4.6-5, 4.6-6, and 4.6-7, respectively.

Figure 4.6-5 shown here is wire size as related to its ampere current capacity and environmental temperature as measured at sea level. Remember that the wire size (or gage) as shown is only true for the AN conductor (see Section 4.6.1). For purposes of clarification only wire sizes AN 24 through AN 6 are shown. Wire sizes 4 to 4/0 have been omitted.

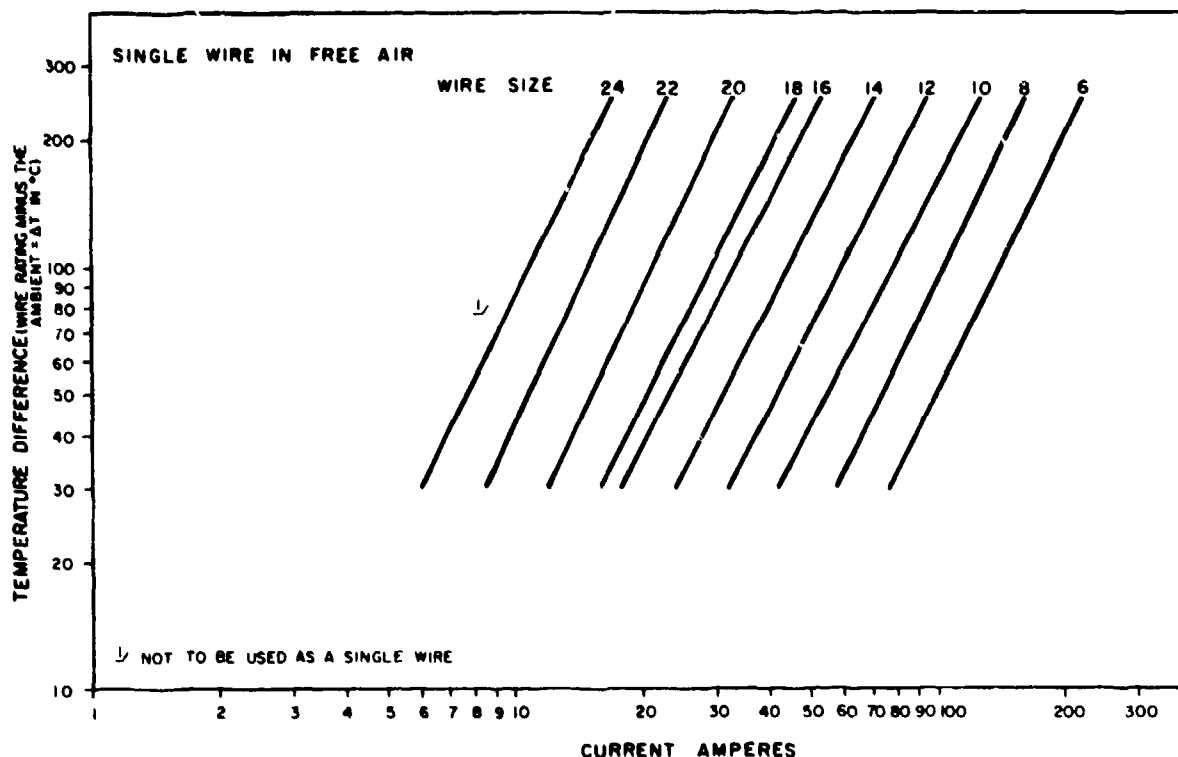


Figure 4.6-5 Single Wire in Free Air

Figure 4.6-6. This is the first time that a complete bundle derating graph has appeared in MIL-W-5088. Prior to this issuance (H), bundle percent loading was fixed at 20%. This new graph now includes 40, 60, 80 and 100 percent loading and has extended the use of this Military Specification.

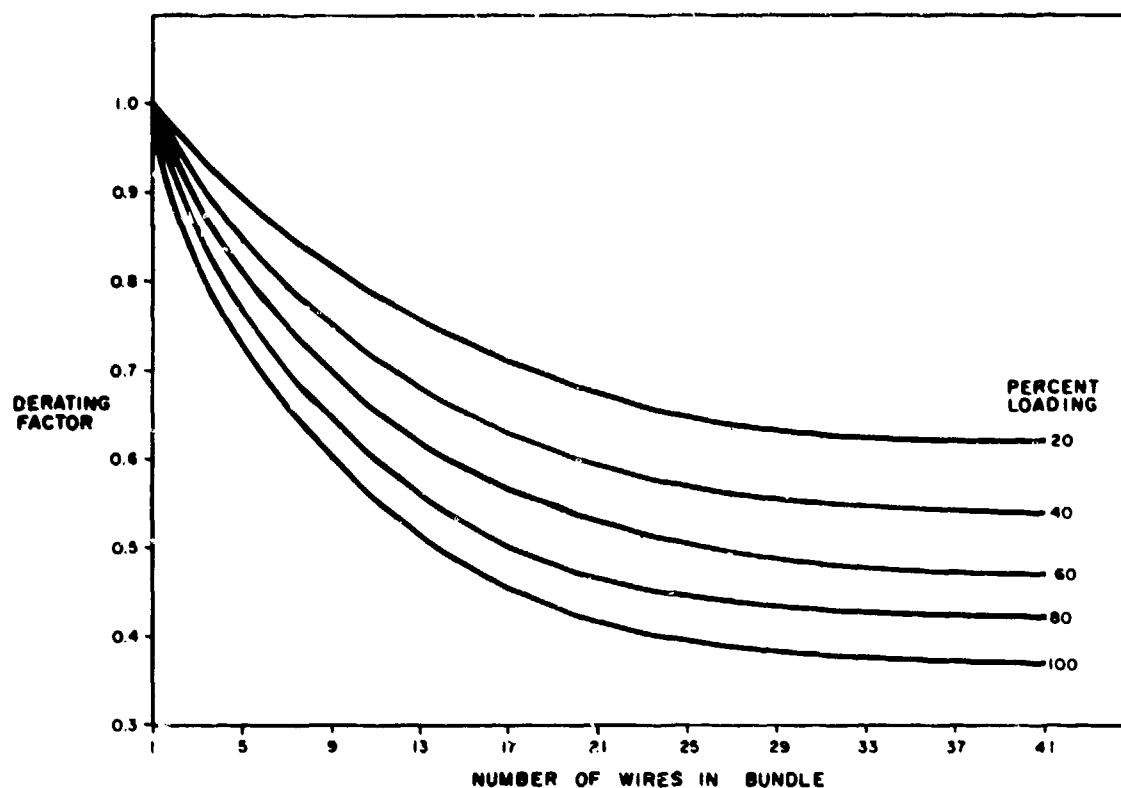


Figure 4.6-6 Bundle Derating Curves.

Figure 4.6-7. The altitude derating graph has been modified to include altitude in meters. The following examples illustrate the use of these three figures.

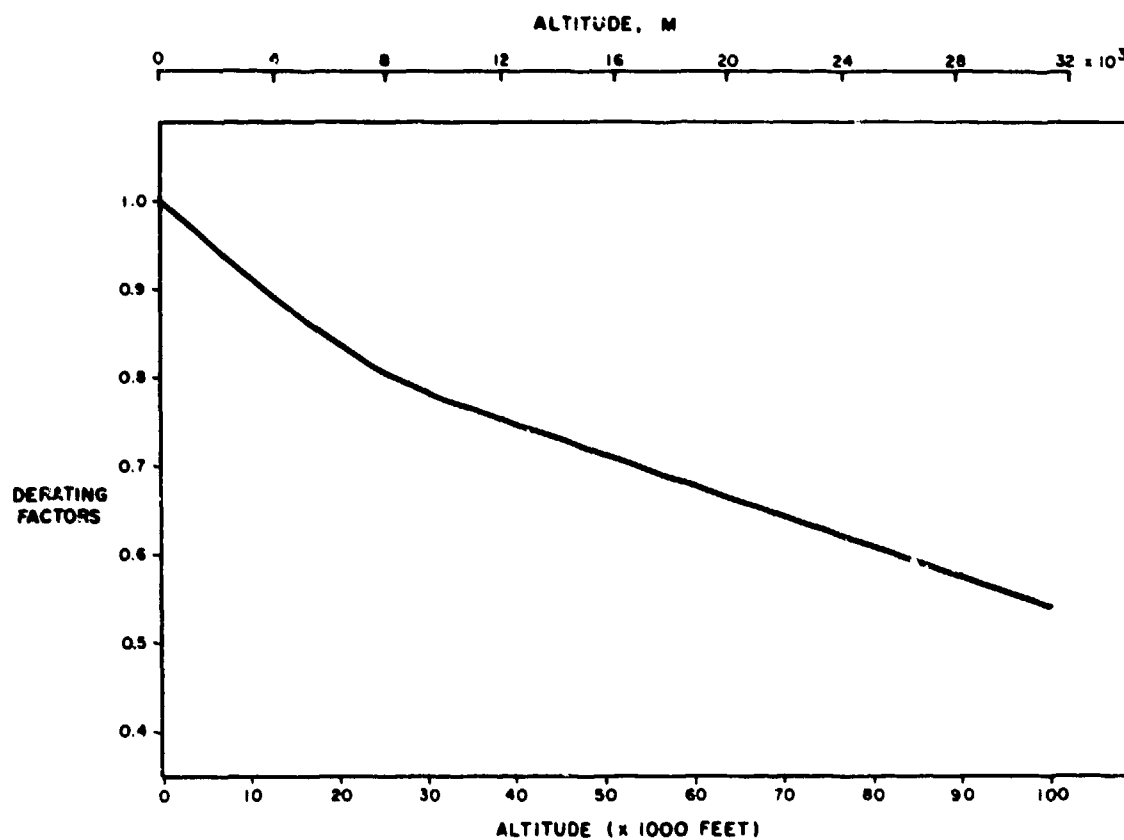


Figure 4.6-7 Altitude Derating Curve

Assume a wiring harness consisting of 12 AN 20, 200° C (392° F) rated wires. The harness will operate in an ambient of 25° C (77° F) at 3 kilometers (10,000 feet) altitude and 110° C (230° F) at 15.2 kilometers (50,000 feet) altitude. All twelve wires will be operated at their maximum capacity. Determine the maximum current capacity of the wiring harness for both altitudes.

a. Referring to the "Single Wire in Free Air" curve in Figure 4.6-5, determine the ΔT of the wire to determine free air ratings.

Example 1: ΔT for 25° C (77° F):

$$200^{\circ} \text{ C} - 25^{\circ} \text{ C} = 175^{\circ} \text{ C} (347^{\circ} \text{ F})$$

Example 2: ΔT for 110° C (230° F):

$$200^{\circ} \text{ C} - 110^{\circ} \text{ C} = 90^{\circ} \text{ C} (194^{\circ} \text{ F})$$

The free air ratings of size 20 wire are:

Example 1: ΔT of 175° C (347° F), use 28 amperes.

Example 2: ΔT of 90° C (194° F), use 20 amperes.

b. Refer next to the "Bundle Derating Curves" shown in Figure 4.6-6. The 100 percent loading curve is selected because each wire is to carry its maximum loading. Next locate 12 on the abscissa since 12 wires are being used and determine the derating factor of 0.53.

c. Now derate the size 20 wire free air ratings using 0.53.

Example 1: 28 amperes \times 0.53 = 14.8 amperes

Example 2: 20 amperes \times 0.53 = 10.6 amperes

d. The wire bundle must now be derated for altitude. Refer to the "Altitude Derating Curve" in Figure 4.6-7.

Example 1: The derating factor for 3 kilometers (10,000 feet) = 0.92.

Example 2: The derating factor for 15.2 kilometers (50,000 feet) = 0.71.

e. Derate the wire bundle further by using the altitude derating factor determined in (d) and the current values determined in (c) above.

Example 1: 14.8 amperes \times 0.92 = 13.6 amperes

Example 2: 10.6 amperes \times 0.71 = 7.5 amperes

f. The total bundle current capacity for example 1 is:

$$13.6 \text{ amperes} \times 12 = 163 \text{ amperes}$$

The total bundle current capacity for the same bundle in example 2 is:

$$7.5 \text{ amperes} \times 12 = 90 \text{ amperes.}$$

The significance of these two examples is the different amounts of current that the same 20 gage wire can carry. The instrumentation engineer has two choices in selecting the wire size for a subsystem installation. Either design to a worst case condition (example 2) or design for a specific need (example 1). The choice is not always easy.

In the previous examples, the installation wiring was specified and supporting calculations were made to determine the maximum current capacity of the wire harness. If the results had been unsatisfactory, new calculations using a different wire size would have been required.

In a situation where existing wiring must be used, the calculations need to be performed in a reverse sequence. Using the previous example of twelve AN 20 gage wires at 15.2 kilometers (50,000 feet) and 110° C (230° F) ambient, if 9.0 amperes of current was required, all other conditions remaining the same, the only design possibility would be to reduce the size of the wire bundle so that it can carry more current. Accordingly, from example 2:

(a) Free air rating of a size 20 wire: For a $\Delta T = 90^{\circ} \text{ C} (194^{\circ} \text{ F})$, the rating is 20 amperes.

(b) Derating the value in (a) by the altitude derating factor: 20 amperes \times 0.71 = 14.2 amperes

(c) Then since the bundle size is unknown use the current value determined in (b) and solve for the bundle derating factor that results in 9.0 amperes. 14.2 amperes \times derating factor = 9.0 amperes.

$$\text{Derating factor} = \frac{9.0}{14.2} = 0.63.$$

A 0.63 bundle derating factor provides for only eight wires in a bundle under these conditions. At this point it might seem reasonable to use the initial design of twelve conductors but separate the wiring into two bundles and then at the connector combine them again into a harness of twelve. This may or may not be a good idea as discussed in the next section.

4.6.5.3 Connector Selection as a Part of Wire Bundle Design

The discussion of the MIL-W-5088H specification thus far has related only to wire gage selection; however, the Military Specification does comment briefly on wire termination devices.

TEST CURRENT

Maximum current ratings of contacts and maximum allowable voltage drop under test conditions when assembled as in service are shown below. Maximum total current to be carried per connector is the same as that allowable in wire bundles as specified in MIL-W-5088.

CURRENT RATING (MIL-C-5015 (G) test method)

Contact Size	Max. Current Rating (amps)	Test Current (amps)	Potential Drop (millivolts)
16	22	13	50
12	41	23	50
8	73	46	25
4	135	80	14
0	245	150	12

Figure 4.6-8 Example of Connector Contact Ratings
Referencing MIL-W-5088. Ref. (4).

The Military Specification is careful to point out that the current ratings in figure cannot be directly applied to connector contacts. However, the connector manufacturer has used MIL-W-5088 as a design aid and has published connector data as shown in Figure 4.6-8.

One of the problems associated with correlating connector and wiring specifications through the use of MIL-W-5088 is that the design changes in one often affect the other. For example, the maximum current ratings shown in Figure 4.6-8, circa 1980, do not correlate with the wire bundle ratings shown in Figure 4.6-10, MIL-W-5088H. The connector manufacturer does, however, have the correct approach to connector selection because one of the most common errors made in selecting a connector is to disregard the effects of the wire bundle configuration. A connector converts all of the wires routed through it into a bundle, particularly high density connectors. Thus, all of the factors that limit bundle configuration should also be considered when selecting a connector.

To assist engineers and designers in the proper application of their connectors, the manufacturer will usually provide useful design criteria information. The time-temperature curves shown in Figure 4.6-9 are an example of the type of information that the manufacturer provides. The characteristics shown in Figure 4.6-9 represents a connector with a shell size 12 and size 20 contacts designed to meet high temperature requirements. Although the information shown represents a sea level environment, the fact that the temperature curve limits are based on a connector contact temperature of 239° C (462° F) permits comparative wire bundle/connector calculations. Assuming the connector to be equivalent to a wire bundle, the effects of the connector dielectric block in which the contacts are positioned will be equated to the wire insulation characteristics. The data supplied by the manufacturer states that the connector will operate satisfactorily at altitudes in excess of 18.3 kilometers (60,000 feet). Example 2 in Section 4.6.5.2.1 will be used as a basis to evaluate this connector.

The wire bundle (connector) consists of twelve wires (contacts) of gage size 20. The contact temperature limitation of 239° C (462° F) will be considered as equivalent to the wire temperature rating shown in Figure 4.6-5. From the previous example the ambient temperature will be 110° C (230° F) at 15.2 kilometers (50,000 feet). As shown previously, 9.0 amperes can be continuously routed through

a wire bundle of eight size 20 wires at 200° C (392° F). The question to be answered is this: If only eight of twelve wires in the bundle could carry 9 amperes, can the connector tolerate all twelve wires in their original bundle form; e.g. eight wires carrying 9.0 amperes and 4 wires carrying 7.5 amperes. The answer is important. If the connector cannot tolerate the continuous current, then a new design approach is required.

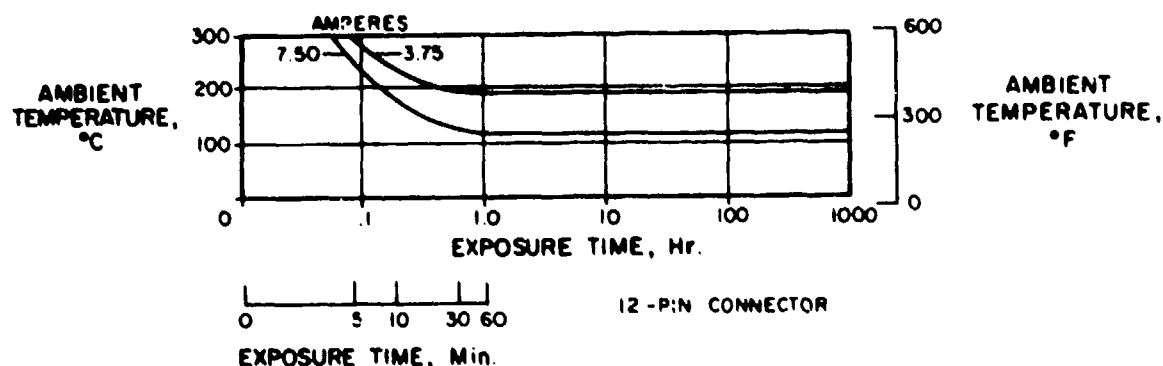


Figure 4.6-9 Connector Exposure Time and Temperature Limitations Based on Contact Temperature of 239° C (462° F).

- (a) Determine the "Single Wire in Free Air" rating:

$$\Delta T = 239^{\circ} \text{C} - 110^{\circ} \text{C} = 129^{\circ} \text{C} (264^{\circ} \text{F})$$

From Figure 4.6-5 obtain the current rating of an AN 20 wire at a ΔT of 129° C, rating = 24 amperes.

- (b) Refer next to Figure 4.6-6 "Bundle Derating Curve" and derate the connector (wire bundle) for 100 percent loading. The derating factor for twelve contact (wires) is 0.53.

- (c) Now derate the "Free Air Rating" of (a) by the bundle derating factor found in (b) above.

$$24 \text{ amperes} \times 0.53 = 12.7 \text{ amperes.}$$

- (d) The connector (wire bundle) must now be derated for altitude. Refer to the "Altitude Derating Curve," Figure 4.6-7. The derating factor for 15.2 kilometers (50,000 feet) = 0.71.

- (e) The first step is to derate the connector (wire bundle) using the bundle derating current value from (c) and the altitude derating factor from (d) above.

$$12.7 \text{ amperes} \times 0.71 = 9.0 \text{ amperes}$$

- (f) The total current capacity for the connector is:

$$12 \text{ (contacts)} \times 9 \text{ amperes} = 108 \text{ amperes}$$

The 9.0 amperes from (e) indicate that the connector can be used to carry the continuous current that required the bundle separation.

One further calculation may be of interest.

It was possible to route eight wires carrying 9 amperes and 4 wires carrying 7.5 amperes through the connector rated in Figure 4.6-9 because the connector was designed to tolerate much higher temperatures than the wiring used.

From the calculations shown in Section 4.6.5.2.1, Example 2, the total bundle current capacity at 15.2 kilometers (50,000 ft) for a 110° C (320° F) ambient was 90 amperes. This 90 amperes can be distributed in any way deemed necessary. For example:

$$10 \text{ wires at } 9.0 \text{ amperes} = 90 \text{ amperes}$$

$$6 \text{ wires at } 9.0 \text{ amperes and } 6 \text{ wires at } 6 \text{ amperes} = 54 \text{ amperes} + 36 \text{ amperes} = 90 \text{ amperes.}$$

As long as the bundling rating of 90 amperes is not exceeded for the same operational conditions, any combination of current ratings not exceeding 90 amperes is satisfactory, although concentrated high-current wiring could cause "hot spots" which should be avoided.

Figure 4.6-10 is a re-printing of Table I as it appears in MIL-W-5088H. It should be noted that this Table is a departure from all previous wire current ratings shown in MIL-W-5088. First, the Table no longer includes single wires and second, the basis for ampere ratings are different as explained in footnote 2.

TABLE I. Current Rating of Wires. ^{3/}				
(See 3.8.8.1, 3.8.8.1.1, 3.8.8.3)				
Conductor material	Wire size	Continuous duty current (amperes) ^{2/} Wires in bundles, groups or harnesses		
		Wire temperature rating		
		105°C	150°C	200°C
Copper or Copper Alloy	1/26	2	3	4
	24	3	4	5
	22	4	6	7
	20	5	8	10
	18	7	11	14
	16	8	12	16
	14	11	17	22
	12	15	22	29
	10	19	30	38
	8	26	39	50
	6	35	53	68
	4	48	72	93
	2	66	100	130
	1	78	115	148
	1/0	89	135	173
	2/0	106	159	203
	3/0	125	186	241
	4/0	146	220	287
1/ Aluminum	8	17		
	6	23		
	4	30		
	2	43		
	1	50		
	1/0	57		
	2/0	68		
	3/0	76		
	4/0	86		

^{1/} The use of these wires requires procuring activity approval.
^{2/} Rating is for 70° C ambient, 33 or more wires in the harness with no more than 20% of harness current capacity being used, at an operating altitude of 60,000 feet.
^{3/} Current rating of wire terminating hardware is not covered by this table.

Notes: 1. Ratings are for copper conductors size 4/0 through size 22 and copper alloy for size 24 through 26.

Figure 4.6-10 Reprint of Table I, MIL-W-5088H.

4.6.6 Example - Selection of a Wire Conductor and Its Insulation Material

Examples of selecting the proper AN gage size of wiring are presented in Section 4.6.5. However, gage selection is only part of the decisions to be made prior to specifying the type of wiring to be used for any given installation.

The following example discusses some of the typical problems encountered as a result of selecting nickel-plated and silver-plated Teflon covered wiring for an aircraft instrumentation installation.

4.6.6.1 Conductors - Because of the installation temperature requirement of 250° C, (482° F) in the engine areas, nickel-plated copper was selected as one of the conductor materials. This material does not solder easily without the use of corrosive fluxes; thus all connections were crimped rather than soldered. The nickel plating, however, alters the ductility of the overall wire, and careful crimping techniques are required to ensure an adequate crimp. Because of required weight restrictions a gage size of AN 24 was selected.

The conductor chosen for the extremely long wire runs in the fuselage was silver-plated copper. This material combination is more susceptible to oxidation than nickel-plated copper, but is somewhat lower in ohmic resistance. The minimum wire size selected for these long wire runs was AN 26, but due to breakage problems, AN 22 wire was finally used. Here again, crimping was chosen rather than soldering for nearly all applications. Because of the weight problem incurred in changing from twenty-six-gage to twenty-two-gage wire, the use of aluminum conductors was investigated. The investigation revealed little development in termination techniques and little or no past experience in aircraft environment. Further consideration of aluminum was discontinued, and the weight penalty was absorbed.

4.6.6.2 Conductor Insulation - Off-the-shelf Teflon PTFE insulation was selected to satisfy the environmental conditions. Teflon insulation has good temperature, dielectric, abrasion-resistance, and chemical resistance properties. A polyimide outer cover was specified for the nickel-coated copper to provide additional abrasion resistance and to inhibit the tendency of Teflon to cold flow.

Some of the problems associated with the wiring were breakage, insulation damage, and radial cracking of the insulation. Breakage and insulation damage were caused by mishandling; however, modified handling procedures reduced the occurrence of breakage. Radial cracking of the insulation was due to incomplete curing at elevated temperature during application of the insulation to the conductor. An improperly cured wire was detected during harness fabrication, and a bend test was developed to detect this deficiency during incoming inspection.

Briefly, this bend test was done by wrapping a short piece of the wire around a tapered mandrel and immersing it in a solution of normal methyl pyrrolidone. An under cured coating appeared "crazed," whereas the properly cured coating did not.

The silver-coated copper conductor was specified as using a production tape-wrap insulation that consisted of two oppositely wound layers of polyimide each with 50 percent overlap. After application of the tape wrap, a dispersion coating of Teflon was applied to provide an environmental seal and a chemically resistant barrier for the polyimide. (This type of construction is available off-the-shelf per applicable Military Specification). Chemical resistance was important because of the presence of engine fuels. Teflon is impervious to engine fuels, but the polyimides are not. However, precautions were taken to use the Teflon-covered conductors in the fuel/engine areas.

During the early stages of installing the completed harnesses in the aircraft a variety of minor problems occurred. Breaking and insulation damage were caused by mishandling, and additional handling procedures were written which effectively reduced these problems. Breakage and insulation damage were checked before and after harness installation by a continuity check and an insulation/resistance check.

A problem of low surface-insulation resistance occurred when the black coloring added to the dispersion coating was found to contain an excess of carbon, which rendered the coating less resistive than the 5 megohms specified in the procurement contract. This did not create problems in the 115 vac or 28 vdc power circuits, but it did create a potential problem to the low voltage caution and warning sensing circuitry. The potential problem exists when the low resistance insulation comes in contact with ground through a resistance path of 4 megohms or less. As shown in Figure 4.6-11, this dispersion coating may make contact with the conductor through the metallic portions of the crimp splice.

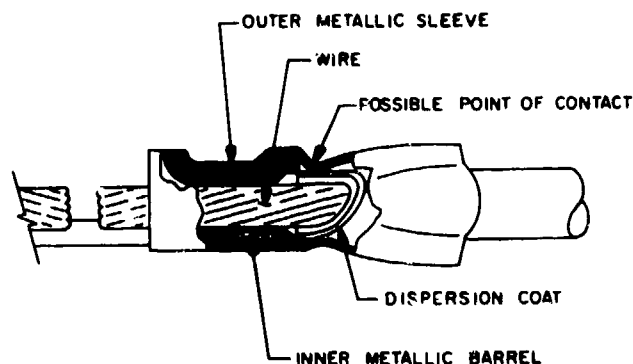


Figure 4.6-11 Crimp Splice Showing Possible Dispersion Coat Point of Contact.

Acceptance testing originally did not include measurement of the dispersion coating. The acceptance testing procedures were modified to include these tests, and no further problems of this type were encountered.

4.6.6.3 Wire Splices - Crimp splices were chosen in lieu of solder splices to achieve better compatibility with nickel-plated wire. During harness fabrication, sample pull tests and careful calibration of all crimping hand tools eliminated the possibility of defective crimping.

Pull tests performed during harness fabrication detected such problems as defective crimping tools, incorrect wire size, and incorrect ferrule sizes. Problems encountered early in the program included inadequate crimping, which allowed the wire to pull out, and overcrimping, which crushed the wire strands and made them brittle and more susceptible to breakage. The problems of crimping techniques were eliminated by providing additional training for the less experienced technicians. Later on in the program the wire splicing was replaced by using modular terminal junctions. (See Section 4.7).

4.6.7 Selection of Flat Cables

Flat, flexible, multi-conductor cable is one of the newer technical advancements in the conductor field. Flat cable can provide a substantial savings in size and weight. It is very flexible and can be folded, bent around corners, twisted, spiralled, accordioned, cemented, or clamped. Flat cable provides electrical properties that can be closely controlled. Flat cable comes in a variety of styles: Laminated or etched, flat or round conductors, with or without shielding. Most of the normally used jacket materials can be supplied as the insulation. Flat cable applications are limited by the fact that the designer must determine and fix his needs permanently, well in advance. Changes cannot be made, or at the least are very difficult to make. Termination methods have been a problem, but non-complicated, reliable connectors, at reasonable prices, are available on the market for use with the more conventional 'standard' flat cables. Ref. (44).

4.6.7.1 Flat Cabling - Definitions

Before discussing the characteristics of flat cabling a basic understanding of the various concepts must be established. The following section will provide flat cabling definitions, some typical comparisons and applications.

4.6.7.1.1. Flat Conductor Cable (FCC)

Flat conductor cable is an electrical cable consisting of three or more solid, rectangular nickel-plated copper conductors. The conductors are embedded in high performance insulating material in a flat and parallel configuration (Figure 4.6-12).

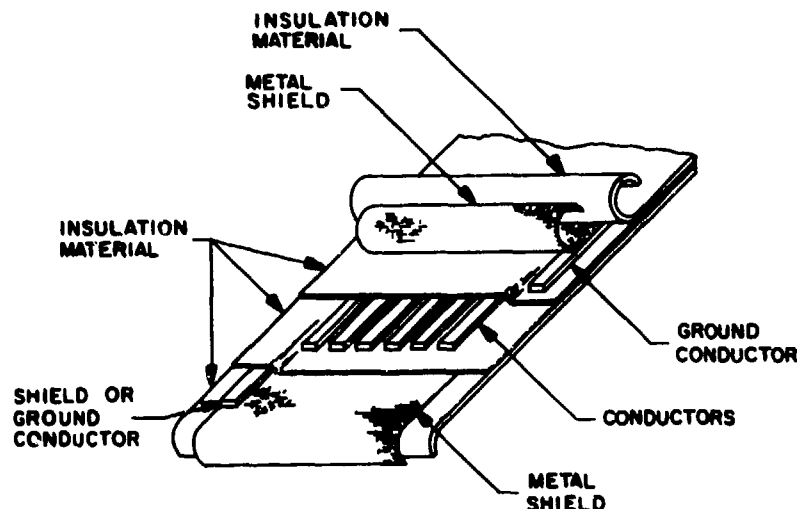


Fig. 4.6-12 Shielded FCC with Offset Edge Conductors

4.6.7.1.2 Flat Flexible Cable (FFC)

Flat flexible cable encompasses all categories of wiring geometrically combined into a flat and parallel configuration. The wire may be round-solid, round-stranded, rectangular (FCC) or etched. The conductors are laminated between thin flexible insulating films and held in a flat configuration (see Figure 4.6-13 and Figure 4.6-14). This type of cable is often referred to as ribbon cable. Ribbon cable, however, is usually of a lighter construction. Ref. (45).

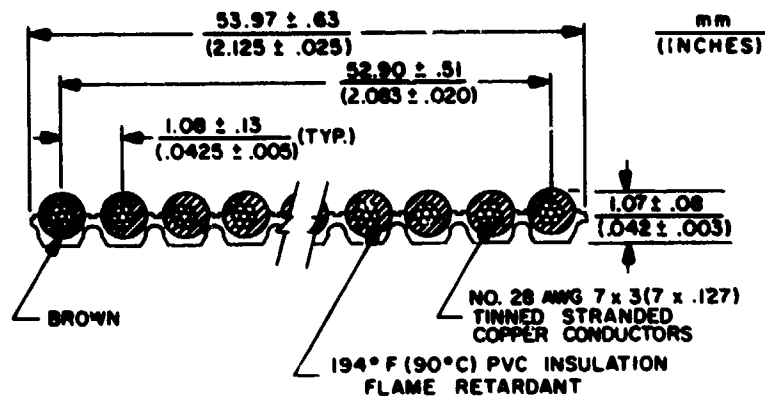


Figure 4.6-13 AWG 28 Stranded Color-Coded Flat Cable (50 Conductors)

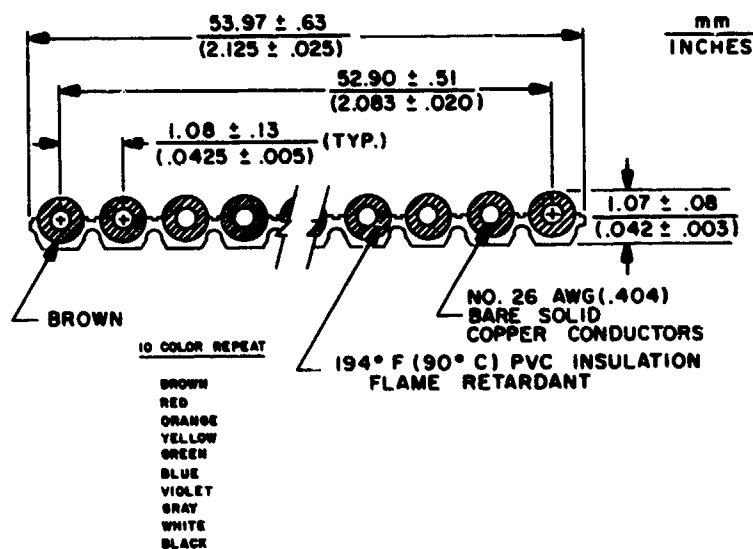


Figure 4.6-14 AWG 26 Solid Color-Coded Flat Cable. (50 Conductors)

4.6.7.1.3 Ribbon Cabling

Ribbon cabling consists of conventional round-solid or round-stranded insulated wires laid side by side and bonded together. Examples are shown in Figure 4.6-15 and Figure 4.6-16. Ref. (47).

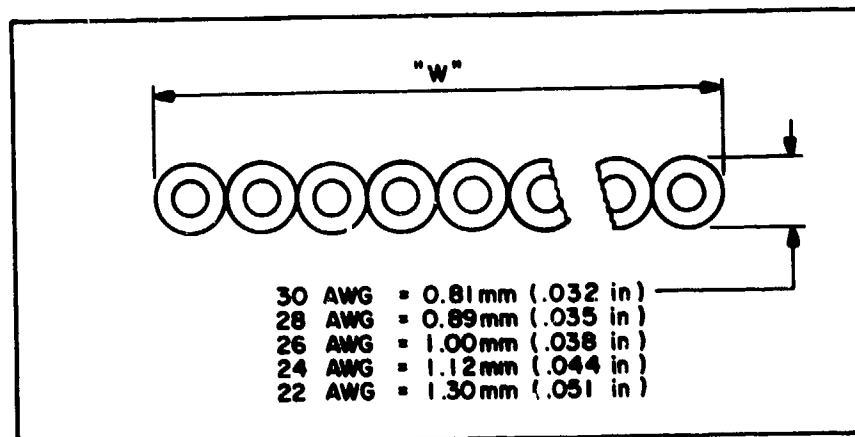


Figure 4.6-15 Stranded Tinned Copper Conductors Insulated and Bonded Together to Form a Ribbon Cable

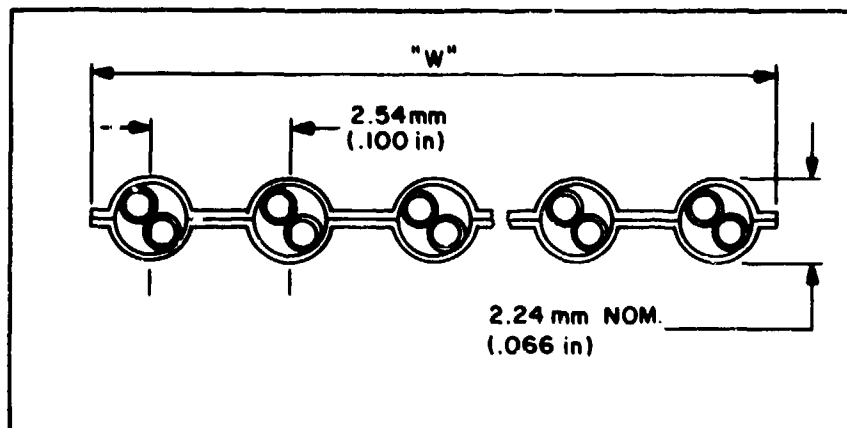


Figure 4.6-16 Stranded Tinned Copper Conductors Insulated and Twisted Into Pairs Formed Into a Ribbon Cable

4.6.7.1.4 Flexible Circuit Board

The flexible circuit board is produced by etching. After the conductors are etched, they are laminated with a protective insulation. The laminate may be as simple as a sprayed-on insulation or a complex conductive shield.

4.6.7.1.5 FCC Capabilities

The space saving feature of flat conductor cables was recognized and first patented in 1884 (note the words "flat conductor"). The advantages of flat flexible cables (which includes FCC) are so many that it is surprising that round cable is still used. Probably the biggest single factor that has retarded its use is the connector. The tedious time consuming factors of stripping and soldering each conductor fairly well offset the savings potential, and wiring mistakes can still occur. However, mass termination methods developed during the last five years or so have pushed the FCC technology into the realm of consideration. Using the mass-termination techniques the connector makes contact with all the conductors of the FCC in one single operation. Two methods are presently available. The crimping technique during which the flat conductor is pressed into a U-shaped channel that cuts through the insulation and then is bent inward until its upper edges dig back into the conductor. Refs. (46, 47, 48)

The other technique is used with both flat and round conductors. Contact is established on the inner edges of a fork that actually cuts into a round conductor and deforms a flat conductor into a U shape.

Shielded flat conductor cable is not as easily mass terminated and, in many cases, a flat-to-round termination is the only flight-qualified method allowed. This is due primarily to the ease of inspection. The method is shown in Figure 4.6-17 (refer to Figure 4.6-12 for shield ground location).

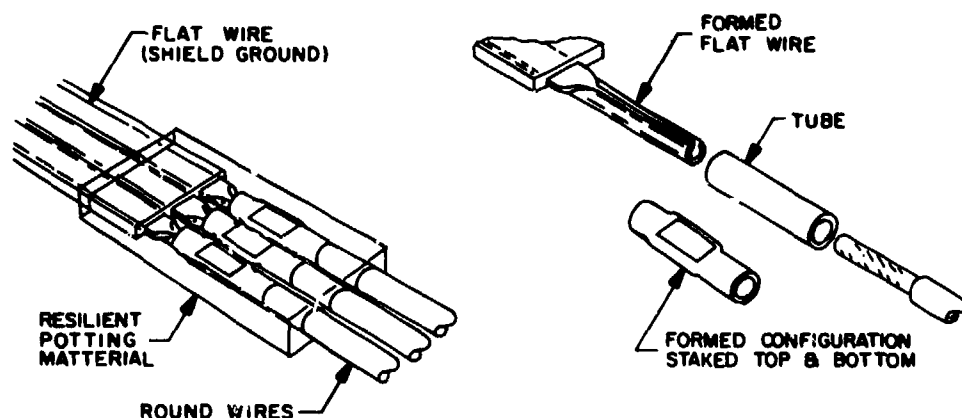


Figure 4.6-17 FCC-To-Round Wire Crimp Transition

In general, mass termination techniques for the FCC such as the ribbon type are rather well established. However, the FCC is less easy to work with and is probably less familiar to the instrumentation engineer.

noting.

The flat cable with flat conductors has some distinct advantages worth

1. Increased surface area is available for cooling; thus, a flat conductor cable can carry more current for the same cross sectional area.
2. More current for the same cross sectional area implies that the required conductor can be reduced in size; less copper means a weight savings possibility.
3. Even though a flat-conductor cable is usually wider than the conventional cable harness, the addition of more conductors requires overall current derating due to temperature rises. The derating though is less for the FCC than for a conventional harness.
4. FCC lends itself to a wide variety of geometry combinations thus facilitating their use as signal lines. For example:
 - a. Interfering signals can be separated by using conductors near each edge.
 - b. Cross talk can be minimized by applying guard wires interspersed with signal wires.
 - c. Application of jacketing material can help reduced cross-talk between FCC assemblies.
 - d. Conductor-less spacers can be used during FCC design to isolate sensitive circuits.

4.6.7.1.5.1 Design Applications - FCC

A high percentage of existing shielded cable in round wire cable (RWC) systems can be replaced by non-shielded FCC by controlling the conductor grouping and harness locations. This is a major advantage of the FCC system, particularly if the instrumentation system is self-contained and isolated. This advantage diminishes as the aircraft systems and instrumentation systems require mutual isolation.

4.6.7.1.5.2 Weight Comparisons

In general, the FCC conductor-contact connector system, developed by NASA/Manned Space Flight Center, provides appreciable weight savings over the current RWC connectors. The primary savings, however, is the cable itself.

Figure 4.6-18 shows a comparison of shielded and non-shielded FCC as compared to a AWG 26 RWC. The savings in weight is worth noting. Notice that two breakpoints exist, one at AWG 24 and the other at AWG 26. The rapid change in slope suggests that the weight savings tend to occur by using the smaller AWG wire sizes.

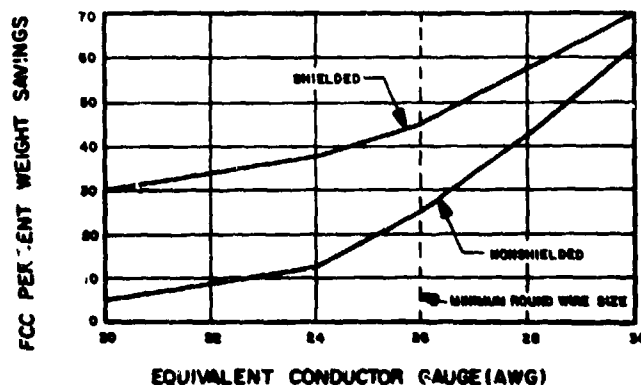


Fig. 4.6-18 Weight Saving Chart, FCC vs. RWC

4.6.7.1.5.3 Space Savings

Space savings is inherent in the geometric cross-section (Figure 4.6-19). Thus, the space savings is minimum for a single bundle but increases rapidly with the number of FCC routed through the same hangers. (See Figure 4.6-20).

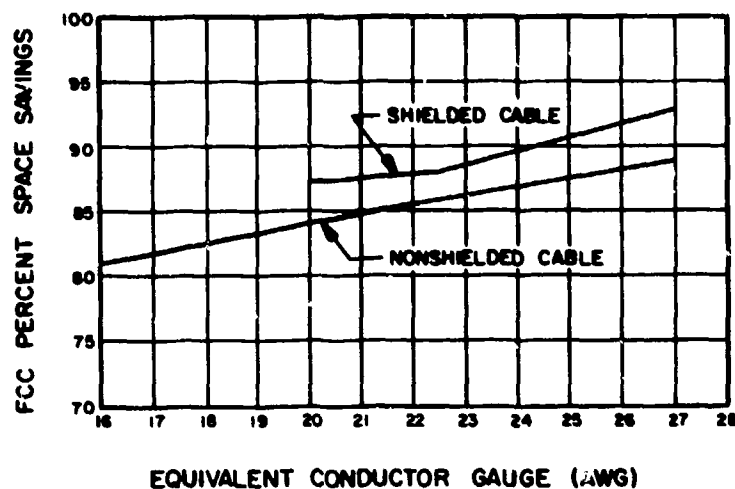


Figure 4.6-19 Space Saving, FCC vs. RWC.

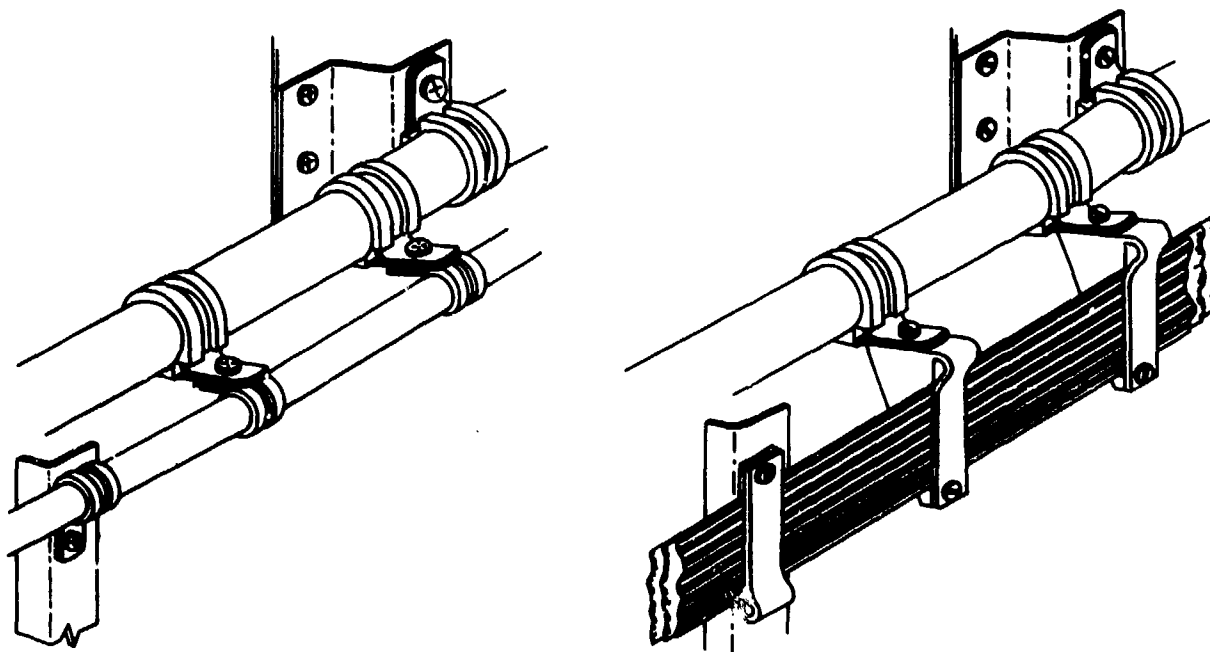


Figure 4.6-20 Space Savings Separation Comparison of RWC and FCC.

4.6.7.1.5.4 Cost Savings

Realistic cost savings can only be derived by including cost of materials (cable, connectors, supports, etc.), design, development, and harness fabrication and installation. These factors are compared in Table 4.6-5.

1. FCC must be applied early in the program.
2. The major cost saving for the FCC is the harness fabrication cost.
3. Connector costs are about the same if the pin-socket type FCC connector is used.
4. The cost savings for FCC increases as the wire size (cross-section) decreases.
5. The cost of clamps and supports for the FCC system is generally less.

Table 4.6-5 Cost Comparison - FCC vs. RWC Systems

Item	Sub-item Percentage Of Major Item	FCC Cost Saving (%) ^a	
		Sub-item	Major Item
Engineering			
System	25	-10	-5
Harness Layout	25	-10	
Production Drawings	25	0	
Schematics, etc.	25	0	
Development			20
Materials			28
Cable	40	0	
Connectors	40	35	
Clamps	5	50	
Supports	15	75	
Harness Fabrication	—		80
Harness Installation			40

a. To realize the cost savings indicated, FCC must be applied early in the program to eliminate redesign, redevelopment, and requalification.

Based on non-programmatic decisions, the cost savings for FCC are only realized for the smaller cross-section conductors. Programmatic inputs, however, may indicate that space and weight are more important. In this case a savings can be well defined as shown in Figure 4.6-21.

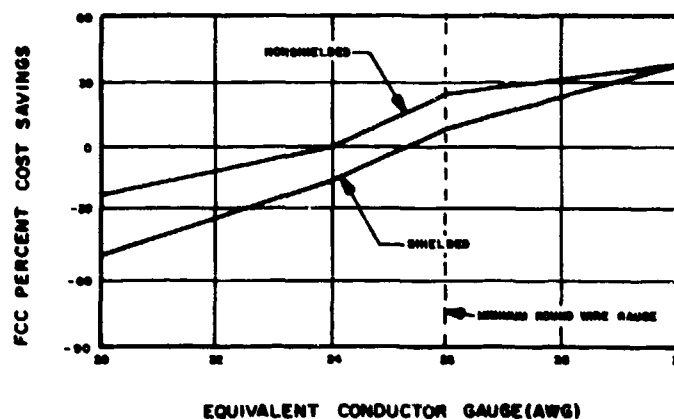


Figure 4.6-21 Cable Cost Savings - FCC vs. RWC

4.6.7.1.5.5 Flat Conductor Re-Routing

Wiring transitions can be effected in two basic ways. First, a flat conductor can be changed to a round conductor and then back to the flat conductor (Figure 4.6-17). Second, the conductors can be re-routed within the FCC (Figure 4.6-22). These changes should be made at a point in the harness where adequate anchoring of the joint is possible. A third method, rerouting within the connector, is possible if it has not been potted.

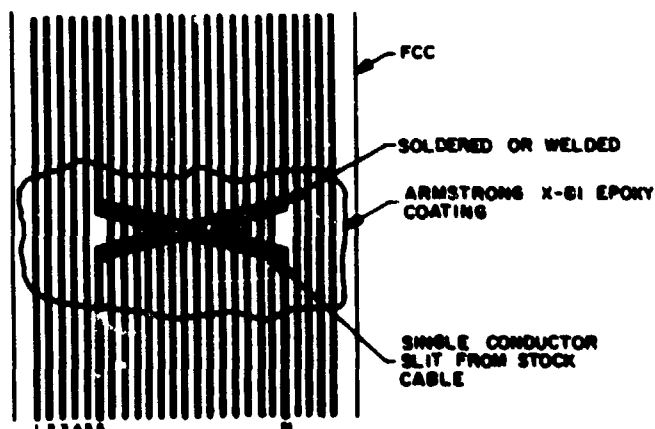


Figure 4.6-22 Re-Routing Conductors Within an FCC.

4.6.7.1.5.6 Reliability and Inspection

The lamination materials used in FCC construction have a tensile strength almost five times that of those used with conventional round wires. Because the flat conductors are laminated this strength is directly added to the conductor, providing an overall cable strength many times that of the conventional round wire conductor (RWC) harness.

The inspection of non-shielded FCC is greatly facilitated by using translucent laminates. This permits visual inspection of the conductors and insulation layers. Many cable faults covered by the opaque insulation of RWC systems are readily apparent in this type of FCC system. Inspection of shielded FCC, however, cannot be accomplished by this visual method.

Two methods are suggested for checking conductors when shielded FCC systems are used.

The first method suggested is a sampling "X-ray check" incorporating a table top radiographic device and a Polaroid camera.

The second method uses a time-domain reflectometer. The time-domain reflectometer is a system utilizing pulse reflections to locate discontinuities along cables. A pulse-by-pulse burst is sent continuously down the cable under investigation and the reflected signals are monitored on an oscilloscope. This method enables the user to view the characteristic impedance of the cable. It will also provide the location and nature of any discontinuity.

Both methods have distinct advantages. Method one will locate laminate problems such as air bubbles and foreign material, whereas method two checks only the conductor integrity.

4.6.7.1.5.7 Usefulness In Flight Test Applications

Briefly, unless the instrumentation installation is sufficiently large, the use of FCC is not an effective technique, particularly on a one-of-a-kind basis. The use of FCC as a packaging technique should be considered for such installations as instrumented wing pods or similar small, self-contained subsystems.

The use of FCC power cables with aluminum conductors offer additional advantages in weight, cost, and availability. However, efficient seals must be developed to prevent corrosion problems associated with the use of aluminum. (See Section 4.6.4.3.5).

4.7 Selection of Modular Terminal Junctions

When terminal junctions were first developed, they were used to replace terminal strips, feedthrough blocks, grounding studs and strips. Each manufacturer designed their own modules and wiring contacts. It was soon recognized, however, that the majority of junctions operated in the same environment as connectors. Accordingly, applicable connector standards were used to further develop the terminal junction capabilities.

One of the advantages of using connector standards is that terminal junction wiring termination can be assembled using crimp contact tooling, thus eliminating unique tooling and support services. With the issuance of MIL-C-39029, proven crimp contact design and the AM standard dimensions were designated, thus standardizing the terminal junction.

The development of the terminal junction has provided the instrumentation engineer with a unique termination. Other components such as switches, relays, circuit breakers, etc., can be designed to accept the same type of contact system using the same connector tooling.

The performance requirements of connectors and terminal junctions should be comparable, since they are used in the same environments. Therefore, the selection criteria for multi-pin electrical connectors can also be used to guide the selection of terminal junctions. Ref. (49).

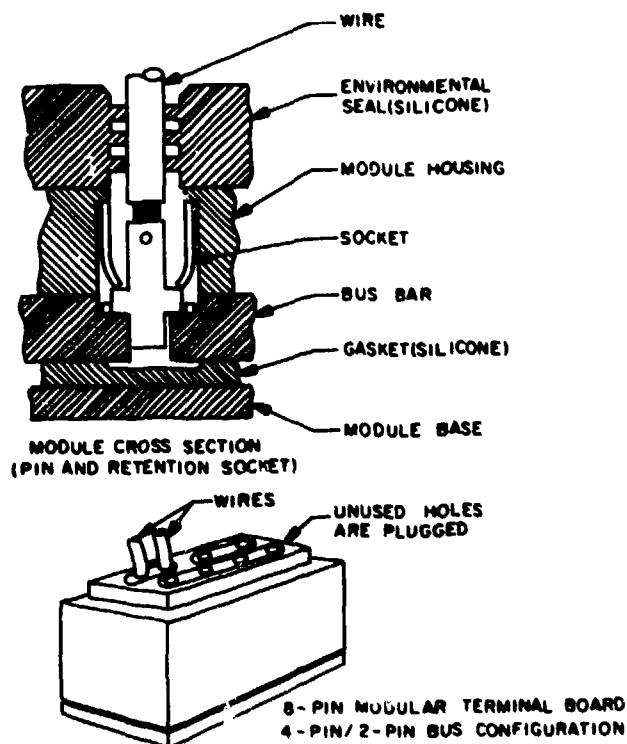


Figure 4.7-1 Typical Modular Terminal Junction.

Since junctions are terminations, evaluation and test methods common to other termination devices should be used to describe and evaluate these items. Most of the standard ratings for environmental connector contact systems apply equally well to junction contacts. Typical requirements can be found in MIL-T-81714, "General Specifications for Terminal Junction Systems." Ref. (50). The selection considerations will be divided into three categories: Electrical, Mechanical and Environmental.

4.7.1 Electrical Considerations

1. Provide Guaranteed Electrical Engagement

To assure adequate contact engagement, connector standards normally define a "minimum electrical engagement" (or electrical overtravel). These dimensions control contact tip location, shape, and "point of first engagement" of the socket pressure member.

This "minimum electrical engagement" is the distance beyond the "point of first engagement" that the full diameter of the pin extends. First engagement occurs when the full diameter of the pin is deflecting the contact pressure member. A minimum guaranteed electrical engagement should be specified that is equal to the requirements set forth in MIL-C-39029 or its equivalent.

Typical installation problems include improper seating of the pins into the block. Although the circuit will "ring through" showing continuity, a slight pull on the wire will remove it from the terminal block. Once the users are familiar with this problem, the proper insertion technique is developed and the problem is eliminated.

2. Provide Stable Contact Resistance

Because the contact system used in junction modules may be different from previous "sockets," the methods used to test its performance should be carefully examined. One example is the need to test for stable contact resistance.

The size and shape of terminal junctions, and the ways in which they are likely to be mounted, make the wire exiting from them susceptible to side pull. To be sure proper contact performance is unaffected, the following points should be considered:

- (a) The forces applied to the wires should be kept below the minimum crimp tensile value for the appropriate contact size.
- (b) Over-exercise of the wire should be avoided if the test is to be performed before environmental testing.
- (c) Dynamic testing of the contact system should be performed regularly to an established criterion.

3. Provide Continuous Dielectric Separation.

Air paths should be prohibited between contacts which are supposed to be insulated from one another. This is a design requirement which could be overlooked in junctions because of the various bussing arrangements used. However, it is an essential requirement. Lack of continuous dielectric separation can lead to corona damage at high altitude, and to moisture entrapment at sea level applications.

4.7.2 Mechanical Considerations

1. Specify the Shortest Practical Contact to Eliminate Bent and Broken Contacts.

Junction contacts should be of the shortest length compatible with good electrical integrity; this makes them less susceptible to bending. They are also lighter, have greater conductivity, and are simpler to inspect.

Requirements should specify the shortest acceptable length. New devices with longer contacts would not present a hazard because they could not be inserted and locked in place in the devices designed for the short pins. However, if requirements call for a longer contact, the shorter contacts will become a hazard, since they may be capable of being inserted and locked in place without providing electrical integrity.

2. Require a Damage-Resistant Internal Contact.

In years past, some connector users found themselves with problems caused by socket contacts that were readily damaged by the insertion of oversized probes, or by bending moments applied to probes mated with the contacts. Two requirements assure users of abuse-resistant contacts.

- (a) Closed-entry socket design.
- (b) Probe-damage resistance, as verified by a test method.

3. Require a Contact System with No Plastic in Compression with the Electrical Joint.

When contact systems are insulated, the insulation should not be used as a functional part of the electrical joint. If contact pressure systems are dependent upon the mechanical strength of plastic parts, they become subject to:

- (a) Catastrophic failure if the plastic distorts because of mechanical or electrical overloads.
- (b) Tolerance problems encountered in the molding of the plastic part which in turn result in a variable contact pressure.

4. Require Redundant Contact Retention Devices

Contact retaining devices should have more than one active member (or "tang"). Experience has shown that two or more tangs can be provided, and the additional reliability inherent in this approach should be a mandatory design requirement.

Single tang systems can induce secondary problems resulting from the non-symmetrical load they impose on the contact. For example, such loading makes it difficult to get a contact removal tool over the contact because the barrel is pushed to one side.

5. Require Vibration Dampening

Junction modules must provide vibration dampening through correct design of wire sealing grommets. This is needed to minimize wire fatigue, as well as to protect the contact system.

When vibration tests are performed on junction modules, the wires exiting from the modules should be clamped to vibrating points on the fixture at specified distances from the modules, rather than attached to non-vibrating points relatively far from the test specimen. The clamping of wire bundles on the fixture itself, at standard distances, more accurately simulates a correct installation and provides more meaningful data.

6. Require Wire Support

Proper grommet design, along with wire supports for larger wire sizes, materially reduces stress on the larger crimped terminations and controls the wire bending. Junctions will be subject to many different modes of installation, and will be handled by many people who have had little or no training. Thus, additional support of the less flexible wire sizes is a desirable safety element.

7. Require Clear and Permanent Identification

A primary function of junction modules is the interconnection of wires installed into equipment. In any such installation, even an untrained operator should be able to recognize the desired termination point. He will find such recognition much easier if all identification markings are standardized.

Standardization of identification should consider the following criteria: marking on grommets, housings, and frames must be clear and remain legible after extended handling, abrasion, and environmental exposure. Markings must resist all common solvents, oils, and fuels. The system should be such that the loss of continuity of the markings cannot result in an altered identification with new meaning. Grommets must be clearly marked to show what electrical circuit arrangement they contain. (Here, permanence of identification is essential.) Markings should be provided on frames (rails and tracks) which will serve to identify rows of contacts in the installed modules.

8. Specify Minimum Weight and Space

The need for space and weight savings is self-evident; in overall system terms, junctions can offer large cost savings by reducing size and weight alone. In evaluating the size of a junction, the overall space occupied by a wired assembly (including access for contact installation and service loops in wires) should be investigated.

9. **Must be Capable of Different Mounting Positions: Wires Perpendicular or Parallel to Mounting Surface**

A major limitation of most conventional terminations is that their attachments protrude perpendicular to the mounting surface. This mounting surface is usually also the mounting surface for the wire harness, which requires the wiring to be brought out to clear the attachments. This clearance requirement results in loss of available space, and at times can present a safety hazard.

Frames (rails and tracks) must provide for mounting junctions in either of two positions:

(a) With wires exiting from modules in a direction perpendicular to the mounting surface (modules upright).

(b) With wires exiting parallel to the mounting surface (modules lying on their sides).

This flexibility in mounting makes possible space saving, optimum access for contact installation or replacement, and shorter (and therefore lighter) wire bundles which exit from the module in the appropriate direction.

10. **Require Flexibility in Busing Arrangements**

Junctions must be so designed that adequate busing configurations are provided. Busing of contacts in rows of four or more rather than in pairs is desirable, since it allows direct replacement of terminal strips or binding posts where the standard practice of attaching three lugs and providing one test point has been followed. One eight-contact module bused in two vertical rows of four contacts each can replace two such binding posts, while permitting wires to exit normally on each side of the junction.

11. **Require Tamper-Proof Confinement of Modules Within a Frame Mounting**

One of the primary advantages of terminal modules over terminal strips and similar devices is that they allow the user to mix modules of varying arrangements and contact sizes. The frames and modules should be so specified that the user can assemble combinations of modules in his manufacturing facility.

12. **Inspectable for Correct Busing after Completion of Final Assembly**

On unsealed terminal strips, a user can visually inspect for correctly bused terminals. A junction module may be a sealed assembly containing a specific busing arrangement which is indicated by exterior marking. One of the worst problems that could be encountered would be for the actual busing arrangement to differ from the one indicated on the exterior surface. For this reason, users must be able to inspect completed modules for correct busing. A 100 percent electrical verification of the busing arrangement indicated should be a mandatory inspection criterion.

13. **Inspectable for Seal Integrity**

Experience in the fabrication of connectors has shown that the junction module grommets must be inspected for seal integrity. The manufacturer should also test finished junctions 100 percent for proper assembly and seal integrity. This may be accomplished by applying air pressure through probes inserted in the wire sealing grommets after final assembly.

4.7.3 **Environmental Considerations**

1. **Require a Contact Rating Which Results in Cooler Operation than the Attached Wire**

A basic design criterion for wiring systems has been to require the contact to operate at a lower temperature than the connected wire. Junction contacts should be free of "hot spots." Materials, plating, and configurations should be such that internal heating due to electrical resistance is less than the attached wire. When junctions contain bused contacts, they should be rated for a specific current load. Each busing arrangement contained within the module should not exceed its maximum rated ambient temperature.

2. **Require Corrosion-Resistant Materials**

Junction modules must be capable of meeting standard corrosion resistance requirements, such as 48-hour salt spray exposure. To assure general compatibility with the surfaces on which they are mounted, standard connector finishes should be used for the mounting frames.

3. Require Fuel and Solvent Resistance

Junction modules are recommended to replace non-environmental resistant devices which cannot be installed, without supplementary protection, in areas contaminated with fuels, oils, hydraulic fluids, cleaning solutions, etc.

4. Require Fully Defined Temperature Ratings

Any discussion of the temperature ratings of a junction must include definition of three basic points:

(a) What electrical loads can they handle at specified maximum ambient temperature?

(b) Is operation at this temperature to be continuous and, if so, what is the estimated life?

(c) Will the device remain environmentally sealed after maximum temperature exposure and continue to meet all performance ratings?

A junction should be rated to carry its maximum electrical load while exposed to its maximum ambient temperature. The temperature ratings specified must be based on the requirement that the device meet all performance criteria after exposure. It is unacceptable to have an environmental part which has lost its seal integrity; such a part may collect moisture.

5.0 INSTALLATION OF THE INSTRUMENTATION SYSTEM

One of the most important requirements of an instrumentation system installation is to insure optimum performance. The system must be installed in such a manner that it will not be subjected to damaging conditions of any kind. From among the many details that must be considered in the installation, several subjects common to all installations have been selected for discussion. These are: (1) the installation of wiring; (2) connector mating; (3) determination of wire bundle size; (4) equipment location; (5) installation procedures that minimize EMI; and (6) some typical transducer installation problems.

5.1 Wiring harness Routing and Installation

Instrumentation wiring may be installed and routed one wire at a time or several at a time. In whatever combination wires are installed and routed, the finished product is a wire bundle or harness. The following section will review the practical considerations to be made during the installation and routing of instrumentation wiring and harness build-up. Ref. (51).

5.1.1 Harness Protection

The first step to be taken in the installation of instrumentation wiring is to verify that the routing areas are ready for the buildup of a wiring harness. Where the wire harness passes near sharp or abrasive surfaces and may come in contact with these surfaces due to movement during handling or flight, the harness must be suitably protected to avoid any damage. Protection must be provided where these conditions exist. Particular attention should be given to bulkhead holes and cutouts, protruding rivets or fasteners, and moving parts.

5.1.1.1 Chafing

Wire harnesses must be protected from damage that may result from rubbing against a surface, an edge, or any other object. Locations of possible abrasion damage (chafing) to the harnesses are:

- a. Where a harness passes around a corner, a shelf, bracket, equipment, or structure.
- b. Where a harness passes through a hole and a clamp or grommet alone is not adequate.
- c. Where a harness is exposed to excessive contact by personnel or equipment.
- d. Where a harness passes near sharp edges of bolts, nuts, or rivets.

5.1.1.2 Moving Parts

Harnesses that are attached to assemblies where relative movement occurs must be installed and protected in such a way as to prevent damage caused by the movement. This includes abrasion caused by one harness rubbing against another or by twisting and bending. Wire harnesses should be routed and/or protective devices installed to provide for permanent wire protection from abrasion and/or other damage. Harnesses should be installed to twist instead of bend across hinges.

5.1.1.3 Protective Grommets and Clamping

Harness protection can be provided by covering sharp protrusions or sharp edges with cushioned material. Where harnesses are routed over or through structural members, caterpillar or split-type grommets can be used as shown in Figure 5.1-1. If the harnesses must be supported to prevent the possibility of chafing, such as may be the case where the hole is much larger than the harness, then cable clamps of the type shown in Figure 5.1-2 must be used. (See Section 5.1.2.4.4.)

If suitable supporting structure is not available for attaching the clamp, the clamp may be attached to lines carrying inert fluids such as nitrogen or water. If an inert line is used for clamp support, then the clamp supporting the wire harness should be attached as close as possible to the clamps supporting the inert line.

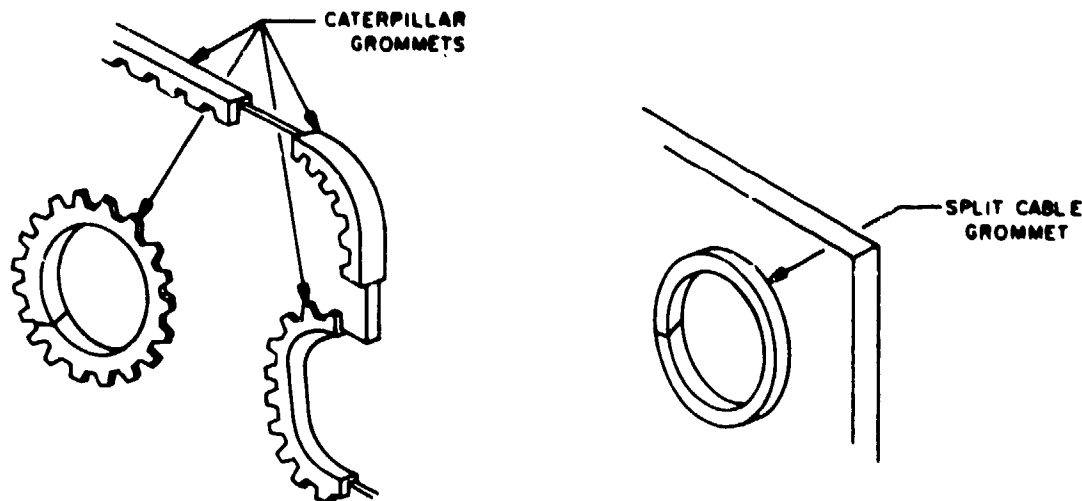


Figure 5.1-1 Protective Grommets

5.1.2 Harness Routing

All electrical wire harnesses should be routed to avoid abrasion, cutting, or piercing of the outer insulation by contact with rough surfaces, sharp edges, or shock-mounted equipment. Harness assemblies clamped to the structure should be routed as directly as possible and protected near entrance areas where the harness is susceptible to use as handholds, steps, or other misuse. Wire harnesses may come in contact with other harnesses provided they are suitably attached and routed to:

- a. Provide accessibility for inspection and maintenance.
- b. Prevent harness deterioration from high temperature or low temperature extremes.
- c. Minimize possibility of damage.
- d. Minimize the need for protective materials.

5.1.2.1 Routing Near Flammable Fluid Lines

An adequate separation must be maintained between harnesses and lines carrying flammable fluids. Where barriers exist that preclude contact between harnesses and fluid lines, the requirements for separation and mounting do not apply. Clamping and securing of harnesses to a pressure or flammable fluid line should not be permitted, although in exceptional cases harnesses in engine areas may be clamped to a flammable fluid line for separation.

5.1.2.2 Routing near Non-Flammable Fluid Lines

Where necessary due to structural characteristics, harness assemblies may be clamped to a non-flammable fluid line for separation. Installations must be separated from non-flammable fluid lines by an adequate distance, which is usually specified in the installation documentation.

5.1.2.3 Slack

Slack in harnesses between clamp installations must be provided to avoid strain on wires/cables in the harness. Slack should be minimized in order to achieve a neat and orderly appearance of the installations, but sufficient slack must be provided for the following purposes:

- a. To permit ease of maintenance, including connector coupling and uncoupling.
- b. To prevent mechanical strain on wires or cables, junctions, and harness supports.
- c. To permit movement of shock-and-vibration isolated equipment.

Slack should not be so great that the harness, under its own weight, or under acceleration or vibration loads, contacts sharp or rough objects that might damage the harness. Movement of the harness by hand should not cause the harness to touch any adjacent surface. Movement by hand is defined as applying sufficient forces to move the harness without visibly distorting or moving the mounting clamps or causing the harness to slide within the clamps. Adequate distance must be

maintained between the harness and any adjoining structure. If the slack permits the harness to come in contact with a sharp or rough object which could cause damage, one or more of the following should be done:

- a. Reduce the slack in the harness.
- b. Increase the distance between the object and the harness.
- c. Provide additional support for the harness.
- d. Add enough protection to the harness and to the sharp or rough object to adequately protect the harness from damage.

5.1.2.4 Harnesses and Equipment Accessibility

Where possible, all wire harness installations should be quickly removable regardless of function, location, or form of electrical connection. All harnesses should be installed so that installation or removal of equipment is permitted. Wire harnesses should never be pulled to facilitate installation, nor to obtain additional slack.

5.1.3 Support Clamping

The primary purpose of clamping is to secure and support the wire harness. Clamps are also utilized to reduce or eliminate vibration, to maintain clearance, and to relieve strain on wire/cable terminating devices, shock/vibration mounts, and other equipment.

5.1.3.1 Clamping Requirements

The standards, specifications, and engineering drawings that apply to installation of wire harnesses should include the clamping requirements for proper harness support. When installing wire harnesses that utilize clamping devices, the following should be considered:

- a. Prevent chafing and wire movement within the support clamp.
- b. Provide clearance when harnesses are routed through or adjacent to bulkheads or structural members.
- c. Maintain proper grouping during routing (see Section 5.4.1)
- d. Prevent mechanical strain that would break wiring, cable, or connections.
- e. Prevent excessive movement under vibration.
- f. Permit free movement of shock/vibration-mounted equipment.
- g. Prevent interference between harnesses and other equipment.

5.1.3.2 Temporary Support Provisions

All wire harnesses should be adequately supported during installation to prevent damage due to excessive bending, kinking, or strain. Such supports should be of a type which will not cause cold flow of wire insulation. Temporary supports for harness connectors must not cause distortion of the wire entry holes in the rear face of the environmental sealing grommet or otherwise result in deterioration of the connector environmental seal.

5.1.3.3 Clamping Devices

In the installation of harnesses, positive locking clamps must be used for harness support. Clamping devices must be of suitable size and type to hold the harness firmly without damage after fastening and without changing the cross-sectional shape of the harness.

5.1.3.4 Clamp Installation

Wire should be supported by clamps as specified on the applicable installation drawing. To insure proper fit, it is recommended that provisions be made to allow deviation of clamp sizes larger or smaller than specified on the installation drawing. Loop type clamps, as illustrated in Figure 5.1-2, should be used.

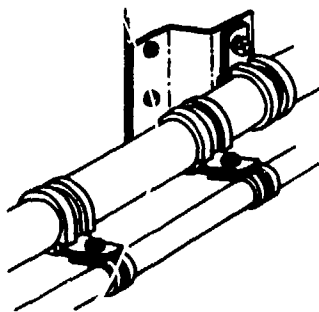


Figure 5.1-2 Loop Type Clamp Installations

The following guidelines are suggested for installing clamps:

- a. The size of the clamp must permit the clamping device to close without deforming.
- b. Washers or other spacer devices should not be installed between the mounting tabs of the clamping device to obtain proper fit.
- c. Deformed clamps should be rejected.
- d. Clamps must be of sufficient size so that the harness is held firmly in place without the need of wrapped sleeving or tape, or the use of filler materials.
- e. Clamp size should be adequate to hold the harness securely in position without being pinched, deformed, or damaged.
- f. Clamping devices must have sufficient grip to prevent sliding or twisting of the wire harness inside the clamp after tightening to the point of gap closure.

5.1.3.5 Clamp Support

Harness assemblies supported by clamps should be secured to the vehicle structure. When harnesses are routed over or through structural members that have grommets or any other protrusions and sharp edges, the harness should be supported by clamping to prevent the possibility of chafing. Where necessary, due to structural characteristics, harness assemblies may be clamped to other harnesses or nonflammable fluid lines for minimum separation.

5.1.4 Cable Shield Terminations

When shield terminations are being made, extreme care must be exercised in selecting the proper method, materials, and tools to assure a reliable connection. All shields that are terminated using ferrule rings must be covered with a snug, flexible, insulating sleeve. For the purpose of this discussion the term ferrule is defined as a ring used to terminate shielding. The ferrule may be of solder or crimp type and is so constructed as to permit attachment of the cable shield(s) and shield return wire if required between the ferrule sleeves.

5.1.4.1 Initial Preparation

Prior to the application of the cable shield terminations, verify that the shield braiding is not cut, nicked, or scratched during removal of the cable jacket insulation. Inspect all termination hardware (i.e., ferrules, insulated solder sleeves, etc.) to assure that the hardware is of the correct type and size and is free of tarnish, corrosion, or obvious damage. Verify that the ferrule placement will be properly staggered to avoid excessive harness diameter buildup and will not exceed the maximum allowable distance from the connector backshell.

5.1.4.2 Shield Terminating Types and Installation

Shield termination of cables can be classified as either grounded or ungrounded, and their installation must be in accordance with the applicable drawings, wire list, or specifications; but the following criteria can be used as a basis for acceptable practices:

- a. Shield terminations should be staggered in order to limit buildup of harness diameter.

- b. Shield terminations must not be positioned in a harness so that they occur under cable clamps or within the potted areas of electrical connectors.
- c. Shield terminations for coaxial cables must be in accordance with the connector manufacturer's instructions, when not specified on installation drawings.

5.1.4.3 Insulation Stripping

When terminating a cable shield, the cable insulation must be carefully stripped from the cable. The amount of insulation removed is dependent upon the shield termination location and length of shield braid required for the ferrule assembly. The removal of jacket insulation must not nick, cut, or damage the shield braid in any way. There must be no evidence of cracked, split, punctured, or damaged insulation on either the conductor(s) or jacket insulation.

5.1.4.4 Location

Cable shield terminations should be located as suggested below and as indicated in Figure 5.1-3.

- a. On connectors with strain relief clamps, the measurement should be made from the back of the strain relief clamp.
- b. On connectors without strain relief clamps, measurement should be made from the extreme back portion of the assembled connector.
- c. On potted connectors, the measurement should be made from the extreme back portion of the connector and/or potted area.

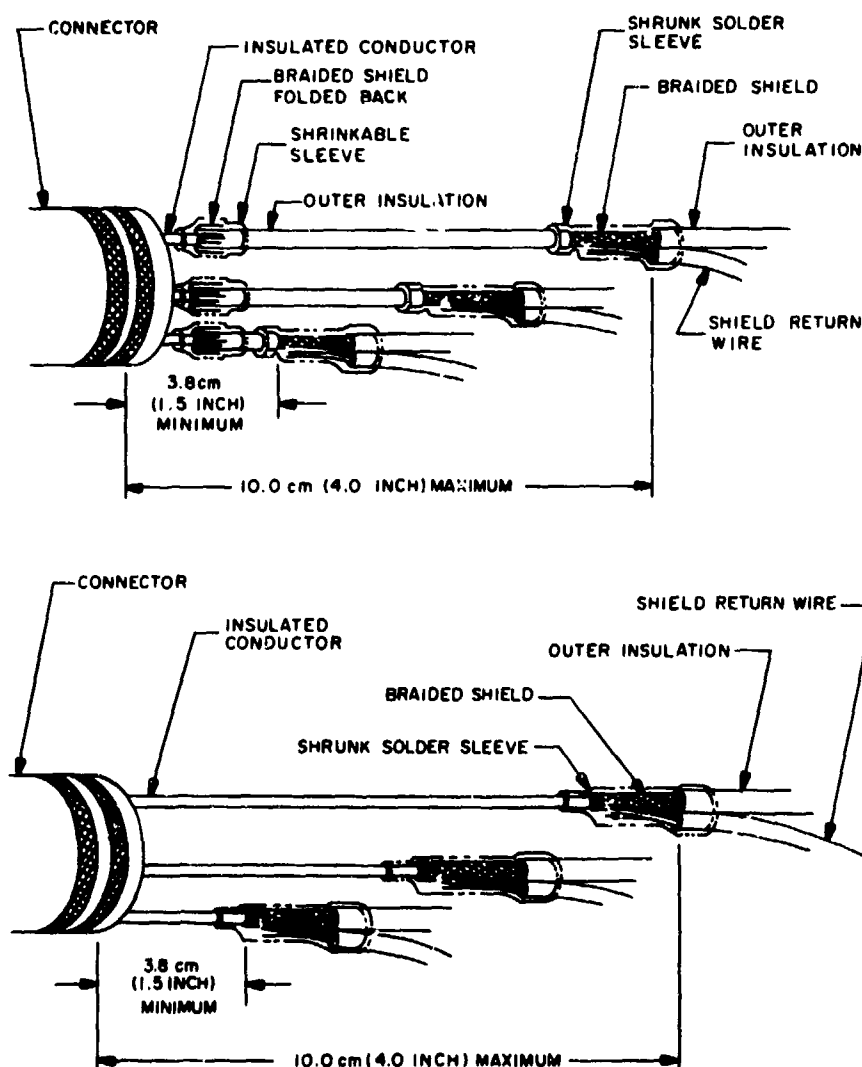


Figure 5.1-3 Solder Sleeve and Related Shield Coverage

5.1.4.5 Shield Return Wires

Where electrical circuit design requires continuity of the cable shield through a connector or to ground, a shield return wire is used. Shield return wires are fabricated from insulated, flexible, stranded type wire with the same temperature rating as the shielded cable. When the insulated wire is to be connected to an electrical connector contact, the wire gage is determined by the contact to which it is being connected; otherwise a minimum wire gage of AWG 22 will be used. Shielded return wires formed by braiding or extending the shielding braid of cable in the form of pigtails should not be used.

The minimum length of shield return wires should be 5 centimeters (2 inches). The maximum length depends upon the staggered locations of the ferrules, but an attempt should be made to keep the length of the shield return wire as short as possible without causing undue tension.

5.1.4.6. Typical Wire Shield Termination

All shielded wires, whether grounded or floating, should be terminated with the application of crimped ferrules or solder sleeve ferrules. There is a wide variety of shield termination designs available. However, two basic types have been selected for illustrative purposes. The first type is shown in Figure 5.1-4. It is a crimp type and is used at the shield end. The second type is shown in Figure 5.1-5. This is a solder sleeve and can be used either at the shield end or at an insulation "window" located between the wire ends. (Ref. (52).

Crimp type end terminations are made of metal and require a crimping tool. For the type of termination that does not have an insulated jacket or sleeve as an integral part of its design, two choices of insulation are available; either "shrink tubing" or the insulation cap made by the manufacturer of the termination. At first thought the use of "shrink tubing" sounds like a reasonable choice, but remember, heat is required to cause the tubing to shrink, and in most aircraft hangars, motorized heat guns are not allowed because of motor sparking. However, the manufacturer's insulation cap, which slides on and locks, can be readily installed with the proper crimping tool.

One disadvantage of the metal crimp type is its sharp thin edges which if not properly handled can nick the wire and cut off strands of the braided shield. However, if the manufacturer's instructions are carefully followed this type of termination is very satisfactory.

The solder sleeve termination can be used either at a window or at the cable end. Window stripping as shown in Figure 5.1-5 allows continuity of the shielding for maximum EMI protection. Another advantage of the window type of termination is that the shield remains intact without cut ends under the heat shrinkable sleeve. The sleeving material, however, tends to cold flow, and under flexing conditions the sharp ends of broken or accidentally cut shielded braid can "work" their way through the sleeving. For the same reason, the solder sleeve must be carefully installed when it is used as an end termination.

The cold flow problem associated with the shield ends can be alleviated by folding the shield back over the insulation jacket. The cable braid must be smooth, flat, and carefully trimmed. Using this procedure locates the smooth braid fold at the area where wire flexing occurs.

As pointed out earlier, the solder sleeve is applied with a heat gun. Thus, all shield terminations must be made during harness buildup in areas other than the hangar if motorized heat guns are used.

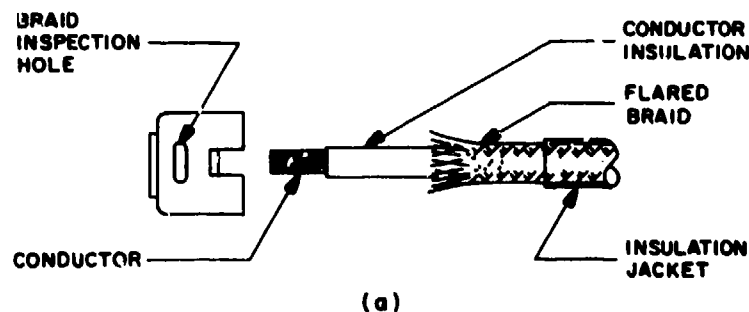
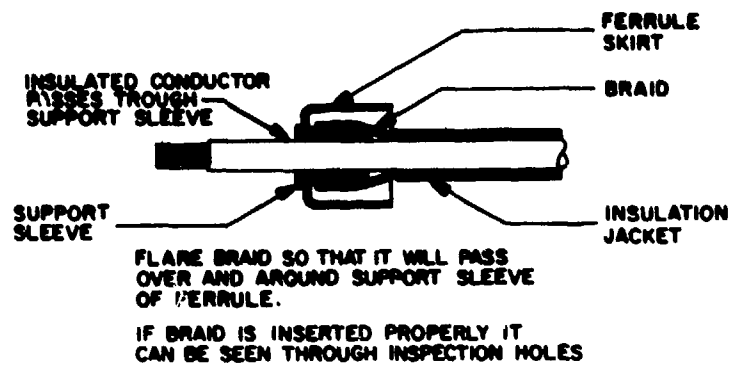
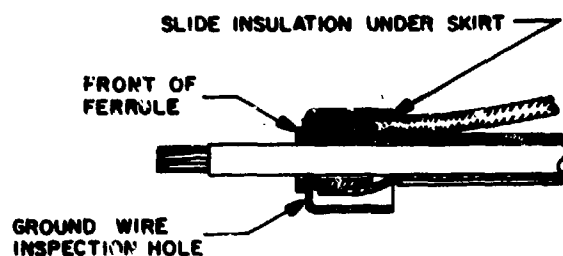


Figure 5.1-4 Crimp Type End Termination



(b)



(c)

Figure 5.1-4 Concluded

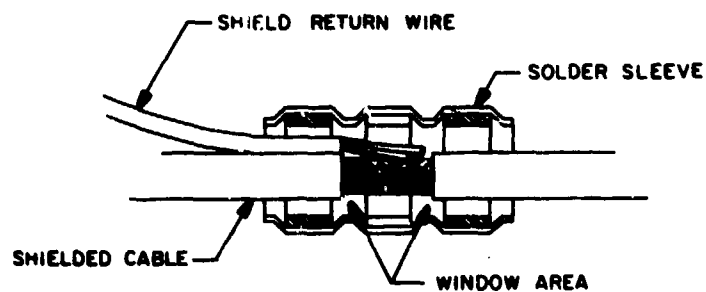
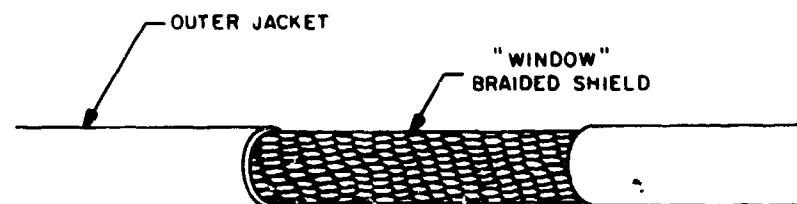


Figure 5.1-5 Application of Solder Sleeves

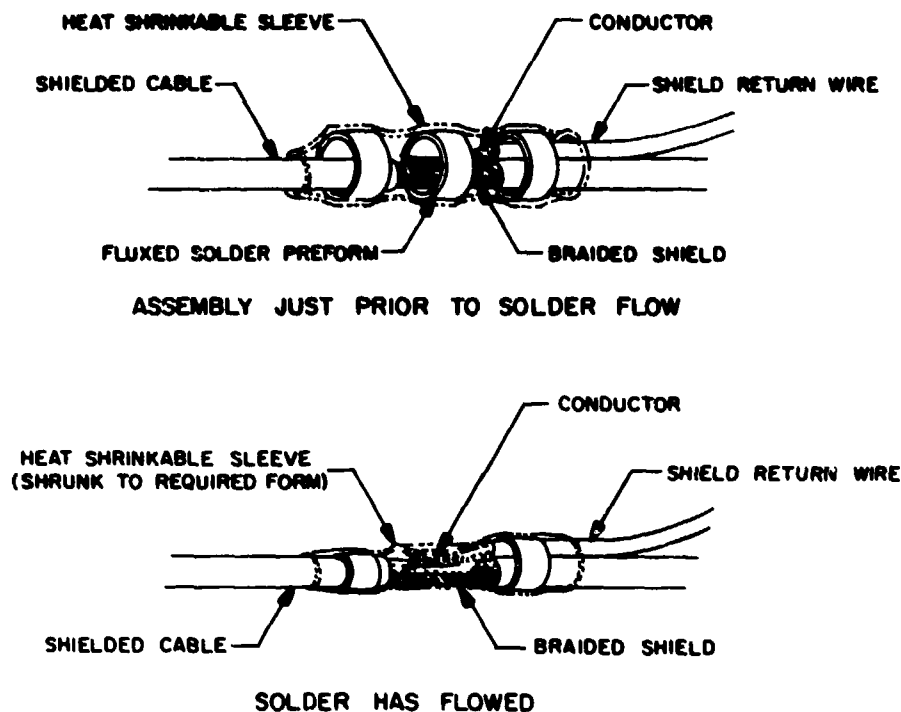


Figure 5.1-5 Concluded

5.1.4.7 Wire Shield Terminations and Connectors

Whenever a wire harness contains many individual shielded wires, in which each shield acts as a Faraday cage, continuity through the mating connector interface is optimized by using an individual connector contact for each shield. This implies that as many contacts are needed in the connector as there are shields. To reduce the number of extra contacts necessary for shield continuity, a technique of looping is sometimes used. In this technique, the single dedicated contact per shield is disregarded. Instead, one contact may carry up to four or five individual wire shields as shown in Figure 5.1-6.

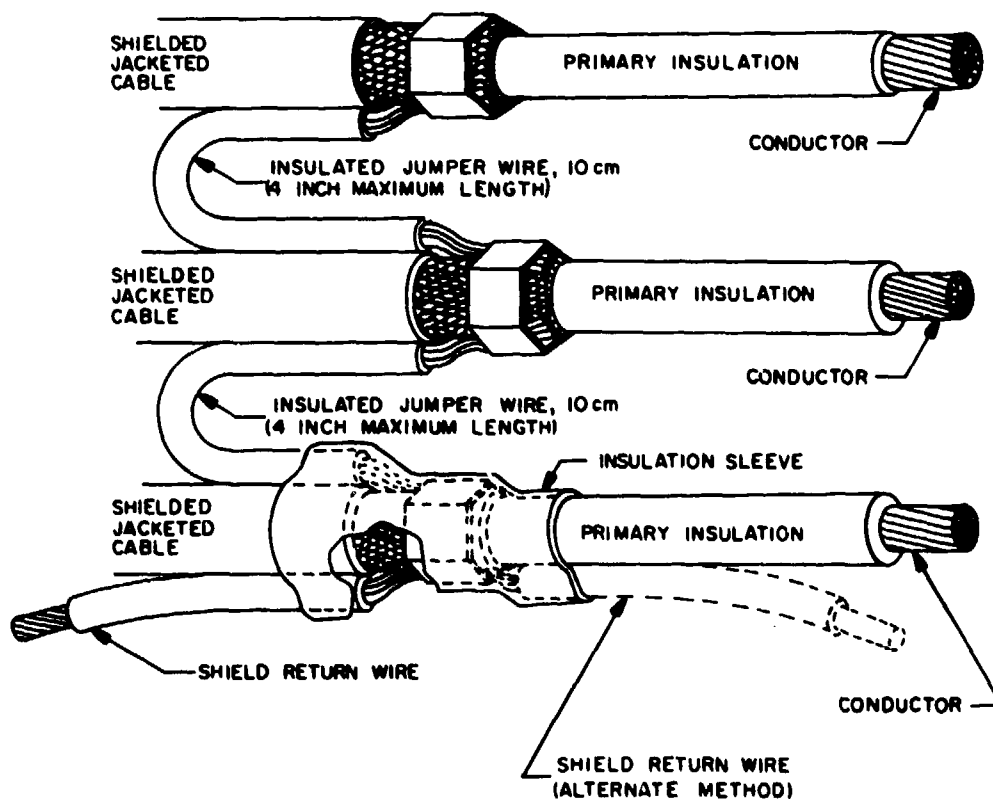


Figure 5.1-6 Terminating Two or More Shields to a Common Conductor

The looping method compromises the Faraday shielding by using short lengths of unshielded wiring as jumpers. Cables carrying signals above one MHz should not use this method, but rather should use a coaxial cable contact or connector.

An improved method of shield termination is shown in Figure 5.1-7. This method eliminates the jumper wire used to loop together the individual shields, thus tending to preserve shielding integrity.

Referring again to Figure 5.1-7, in part A, the braided wire pigtail for each shielded wire is folded over the inner ferrule, flattened and evenly distributed about its periphery, as shown in B. In the next step, C, the stripped and fanned end of the shield return wire is placed under the outer ferrule in contact with the braided shields, and the outer ferrule slides into position over the inner ferrule. The assembly is crimped, and a shrinkable insulation sleeve is placed over the ferrule and shield return wire as shown in D.

One of the advantages of this method is that it permits much shorter unshielded conductor lengths with a minimized buildup of the harness diameter.

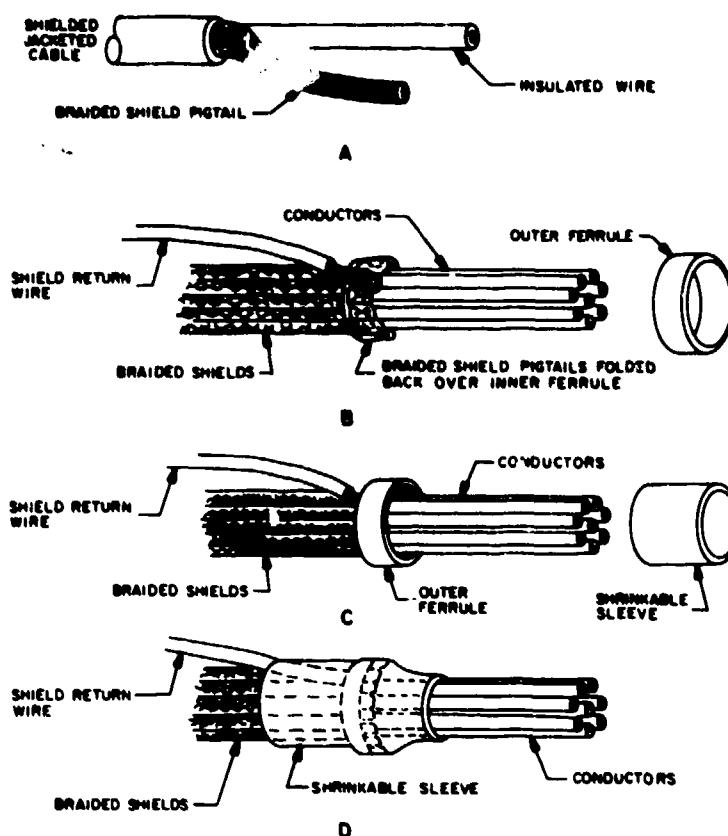


Figure 5.1-7 Shield Termination Using an Outer Ferrule Ring

5.1.5 Connector Mating

Where similar connectors are used in adjacent locations, the wire harnesses should be routed and supported in such a way that improper connections cannot be made. When this requirement cannot be accomplished by routing, special connectors, identification, or procedures must be provided to ensure proper connector mating.

The mismating of a connector is a human error, and an examination of its occurrences always reveals additional human errors. For example, on one occasion, the cables to the yaw-rate and pitch-rate gyros were interchanged in the control system of a drone vehicle. The interchange occurred after the cables were disconnected to enable a battery to be replaced after the system was checked out and before a mission was flown. The connectors were mismated and then not inspected. It was erroneously assumed that the proper connections would be made after the battery was replaced.

The problem of connector mismating can be minimized by advance planning and design. There are several ways to prevent connector mismating, but the most common is connector polarization.

5.1.5.1 Connector Polarization

Connector polarization consists of arranging the connector shell, the insert configuration, or both, in such a way as to prevent connector mismating. Polarization should be used throughout an instrumentation system. Ref. (53).

5.1.5.1.1 Insert Rotation

A rather common technique of polarization varies the orientation of connector insert within its shell, as shown in Figure 5.1-8. Rotating the insert with respect to the shell results in several different pin and socket configurations, of which no two are alike. Figure 5.1-8 illustrates several configurations created by rotating the inserts at different intervals. The choice of rotation interval is specified by the manufacturer. Others besides those shown may be used, such as 20°, 25°, 30°, and so forth.

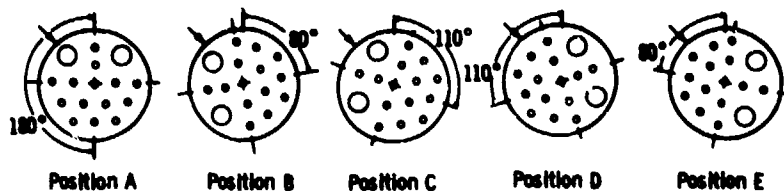


Figure 5.1-8 Polarization Achieved by Insert Rotation

At first glance, the rotation of the inserts appears to provide a satisfactory solution to the connector mismatching problem. Yet, even rotated insert connectors can be mismatched if the insert is of soft material. Oftentimes brute force is used to make connector couplings, and under these circumstances, pins can be forced into the soft connector insert material.

5.1.5.1.2 Shell Keying With Round Connectors

One of the better and more commonly used methods for the prevention of misconnection is the use of keys and keyways to align the two mating connector shells. Of course, the connectors must be correctly assembled in order to take advantage of the polarizing concept. A typical combination of keyways is shown in Figure 5.1-9. Seven locations for the main or polarizing keyway are shown. The polarizing keyway is the wider one. The other narrower keyways usually remain fixed in the positions shown. This method of polarization relies solely on keyway configuration, since the orientation of the insert remains the same. However, insert keying can also be used in combination with insert rotation, providing a wide variety of polarized configurations. Again, however, the connectors can be mismatched if the socket insert material is soft.

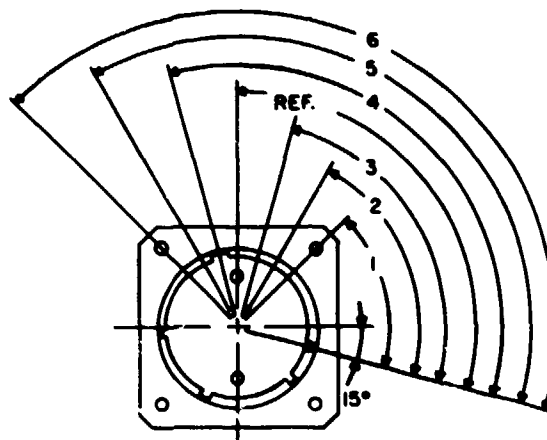


Figure 5.1-9 Shell Keying a Round Connector.

5.1.5.1.3 Shell Keying With Rectangular Connectors

The stud and slot arrangement identified by the arrows in Figure 5.1-10 exemplifies a simple but effective way to prevent connector mismatching. This polarization method can be implemented in dozens of ways, and, if necessary, fabricated by the user.

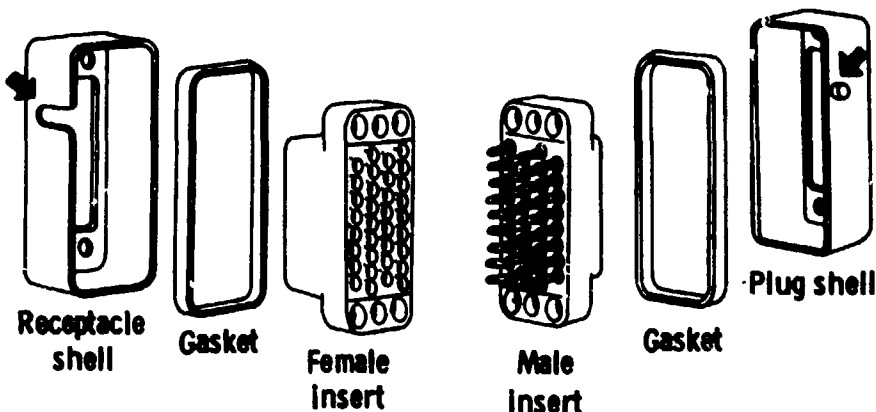


Figure 5.1-10 Shell Keying a Rectangular Connector.

5.1.5.1.4 Corner Polarization

Figure 5.1-11 shows another polarizing technique that can be used with rectangular connectors. There are polarizing nuts in four corners, and the nuts can be polarized in different ways, providing dozens of different polarizing combinations. Correct assembly is required for proper mating of the polarized shells. Notice in Figure 5.1-11 that the polarization post locations A and B provide the matched nut-pairs 1-4, 4-1, 2-5, 5-2, 3-6, and 6-3.

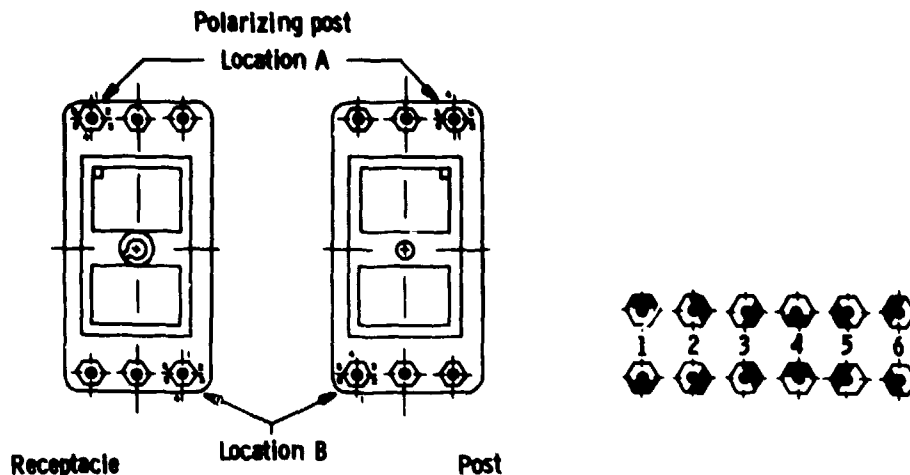


Figure 5.1-11 Corner Polarization

5.1.5.1.5 Other Ways to Prevent Connector Mismatching

Insert rotation and keyway mating techniques add to the cost of the basic connector; as a result, other, less effective methods are often used.

1. Harness Restriction

During the wiring of a system, the cable to each connector can be tailored in length to prevent it from being mated with any connector other than the one intended. This method is effective if the connector couplings are far enough apart to prevent the cable length from being changed by brute force.

2. Variations in Connector Size and Shape

Using various connector sizes is an excellent way to prevent mismatching. However, the use of different connector sizes is not always practical, because attempts to mate different sized connectors oftentimes bend the pins. Less important, the larger inventory of connectors means that the advantages of standardization are lost. Similarly, a mixture of rectangular and round connectors can be used. Before this technique is used, however, the resulting inventory buildup should be carefully considered.

3. Blocking Pins in the Socket Insert

This method makes the best use of the standardization concept and minimizes inventory buildup. Certain contact sockets are blocked, thus preventing a pin contact from entering. Only those plugs and receptacles with the proper pin-socket geometry will mate. Blocking pins can be used to advantage on identical pieces of equipment that are installed side by side.

5.1.6 Connector Inspection

Immediately prior to mating, examine each connector to ensure that:

- a. The insert faces are clean and free of chips, dirt, or any other foreign materials that would damage the pins, or that would prevent them from easily entering the socket.
- b. There are no bent, damaged, or misaligned pins or sockets, nor any splits, cuts, gouges, or other damage to the insert.
- c. The pins or sockets are not abnormally recessed or extended.
- d. There are no nicks or fractures in the connector shell or inserts.
- e. The plating is free of flaking, porosity, or roughness.

- f. Connectors with removable "O" rings, seals, or grommets are properly installed in the connector halves prior to mating.
- g. Connectors are properly marked so that the "P" and "J" numbers match, and pin and socket configurations are compatible.

Caution should be exercised when mating connectors so that damage does not occur to connector pins or sockets. Under no conditions should connectors and their harnesses be subjected to undue manual force during the installation process. The following precautionary procedures must be adhered to:

- a. There must be adequate wire length for bundle flexing during connector coupling and uncoupling.
- b. Wire harnesses (excluding coaxial cables) must not be twisted more than one-quarter turn between a connector and the first clamp when aligning connector keyways, and should an additional one-quarter turn be required, this required twist must be made between the other support clamps. Coaxial cables must never be twisted during mating operations.
- c. Wire bundles must not be pulled to obtain the required length needed to complete the mating of connectors. Appropriate slack between the connector and first clamp should be assured prior to connector mating.

5.1.7 Connector Protection

All connectors should have protective caps installed throughout all stages of fabrication and installation, except when mated. The caps provide both environmental and physical protection and are usually a standard requirement for all plugs and receptacles. However, most metal protective covers are made of aluminum, and experience has shown that the cross-threading or gouging of the protective cap tends to produce metal particle contamination. This problem can be avoided, however, by using plastic covers. Most plastic covers are made of polyethylene and are somewhat flexible. Plastic covers of a slip-on design are used extensively by the connector manufacturers as protective covers during shipment but should not be considered as a substitute for the metal cap design. Plastic caps similar to the metal caps are also made and are available for threaded or clamp connectors. These types of caps can be considered a substitute for metal caps. A common and highly satisfactory use of the plastic protective cap is in the stowing of unused wired electrical connectors. In most flight test environments, it is standard practice to place a plastic cap on each connector and then wrap the connector in protective tubing that is subsequently tied shut.

Whether the protective cap used is metal or plastic, it must, as a minimum, fulfill the following requirements:

- a. Protect the electrical contacts from damage.
- b. Protect the connector threads or locking studs from damage.
- c. Be highly resistant to abrasion and cracking.
- d. Be brightly colored so as to be highly visible.
- e. Fit the plug or receptacle tightly.
- f. Be easy to install and remove.

5.2 Determination of Wire Bundle Size

The installation of instrumentation and its wiring usually requires careful fit checks of the components, hardware, and cable bundles. The problems of routing wire bundles through existing bulkhead access holes and other similar areas of restricted space can be made easier if the size of the wire bundle designed on paper can be estimated. The following formula and sample calculations illustrate a useful method for estimating wire bundle size. Ref. (54). The estimation is:

$$D = 1.13 (d^2 N)^{\frac{1}{2}}$$

where

D = diameter of bundle

d = diameter of cable or wire

N = total number of each wire of diameter (d) used in the bundle

Example (1): A typical case is the calculation for a twisted-shielded pair.

The cable cross section is oval with a twist rather than round, and when measured for the value (d), two values are obtained: The maximum value in this example is 0.61 centimeter (0.24 inch), the minimum value is 0.41 centimeter (0.16 inch).

For the calculation the maximum value will be used:

Example 1: Let $N = 40$ total (twisted-shielded pairs)

$$d = 0.61 \text{ centimeter (0.24 inch)}$$

$$\begin{aligned} D &= 1.13 \left[(0.61^2) \times 40 \right]^{\frac{1}{2}} \\ &= 1.13 \times 3.86 \text{ centimeters} \\ &= 4.36 \text{ centimeters (1.72 inches)} \end{aligned}$$

The circumference equals πD , where π equals 3.141 and $D = 4.36$ centimeters (1.72 inches). Therefore, the calculated circumference is equal to 3.141×4.36 centimeters, or 13.7 centimeters (5.4 inches). The measured circumference is equal to 13.2 centimeters (5.2 inches).

This formula is also valid for wires and cables of mixed sizes:

Example 2: Consider a wire bundle consisting of two different size wires:

$$(a) \quad d_1 = 0.14 \text{ centimeter (0.054 inch)}$$

$$N_1 = 25 \text{ wires}$$

$$(b) \quad d_2 = 0.61 \text{ centimeter (0.24 inch)}$$

$$N_2 = 16 \text{ wires}$$

Total the values d^2N :

$$(a) \quad (0.14)^2 \times (25) = 0.49 \text{ cm}^2$$

$$(b) \quad (0.61)^2 \times (16) = 5.95 \text{ cm}^2$$

$$\text{Total} = 6.44 \text{ cm}^2$$

Then;

$$D \text{ total} = 1.13 (6.44)^{\frac{1}{2}} = 2.87 \text{ centimeters}$$

$$\text{calculated circumferences} = \pi \times D$$

$$= \pi \times 2.87 \text{ centimeters}$$

$$= 9.01 \text{ centimeters (3.55 inches)}$$

$$\text{Measured circumference} = 8.9 \text{ centimeters (3.5 inches)}$$

5.3 Equipment Location

Many equipments are sensitive to shock and vibration forces, and it may be impractical to rely solely upon an isolation system to reduce the forces to within tolerable limits. This is especially true at locations within the aircraft that experience high levels of shock and vibration. Because of this, it might be an advantage in some cases to consider changing the location of the equipment to a part of the aircraft that puts less of a requirement on the equipment. This procedure requires that a complete shock and vibration analysis be made to determine the levels that exist at suitable locations within the aircraft. Examples for an F-104 aircraft will illustrate the procedure. Refs. (55, 56).

Table 5.3-1 Correlation of Vibration Categories with F-104 Aircraft Locations.

CURVE	APPLICATION
A	<ol style="list-style-type: none"> 1) EQUIPMENT NORMALLY INSTALLED ON VIBRATION ISOLATORS BUT TESTED WITH RIGID MOUNTING, DUE TO UNAVAILABILITY OF ISOLATION. 2) EQUIPMENT MOUNTED ANYWHERE IN UNPOWERED GLIDE VEHICLES (UNLESS VEHICLE IS CARRIED ATTACHED TO OTHER AIRCRAFT, IN WHICH CASE LOCAL ENVIRONMENT IMPOSED BY THE CARRIER AIRCRAFT MUST BE CONSIDERED).
B	<ol style="list-style-type: none"> 1) EQUIPMENT MOUNTED IN FUSELAGE FORWARD OF CG EXCEPT WHEN ENGINE IS MOUNTED IN FORWARD FUSELAGE. 2) EQUIPMENT MOUNTED IN FUSELAGE AFT OF CG EXCEPT WHEN ENGINE IS MOUNTED IN AFT FUSELAGE. 3) EQUIPMENT MOUNTED IN WING INBOARD HALF OF SEMI-SPAN EXCEPT WHEN ENGINE IS WING MOUNTED.
C	<ol style="list-style-type: none"> 1) EQUIPMENT MOUNTED IN THAT SECTION OF FUSELAGE FORWARD OF AFT OF CG IN WHICH ENGINE IS MOUNTED. (EXCEPT ENGINE COMPARTMENT, SEE "D"). 2) EQUIPMENT MOUNTED IN WING OUTBOARD HALF OF SEMI-SPAN. 3) EQUIPMENT MOUNTED IN WING TIP PODS. 4) EQUIPMENT MOUNTED IN ANY WING IN WHICH ENGINE(S) ARE MOUNTED.
D	<ol style="list-style-type: none"> 1) EQUIPMENT MOUNTED INSIDE THE ENGINE COMPARTMENT OR ENGINE PYLON. *
E	<ol style="list-style-type: none"> 1) EQUIPMENT MOUNTED DIRECTLY TO ENGINE. (NOTE: ENGINEERING MAY PRESCRIBE A LESS SEVERE TEST BASED ON SPECIFIC DATA ON A GIVEN ENGINE INSTALLATION IF SUCH DATA IS AVAILABLE).
F	<ol style="list-style-type: none"> 1) EQUIPMENT MOUNTED IN HELICOPTERS (EXCEPT FOR ENGINE COMPARTMENT OR MOUNTING DIRECTLY TO ENGINE, IN WHICH CASES COMBINE "F" WITH "D" OR "F" WITH "E" RESPECTIVELY, USING THE HIGHER VALUES FROM EACH OF THE CURVES. 2) THE LOWER FREQUENCY PORTION OF CURVE "F" (5 Hz TO 32 Hz) IS COMBINED WITH THE PORTION OF CURVE "C" ABOVE 32 Hz FOR EQUIPMENT MOUNTED IN POWER OPERATED RUDDERS, ELEVATORS OR AILERONS.

* Certain boundary conditions will exist where equipment is mounted in one compartment, but extends into another, or may be mounted on the engine compartment bulkhead or firewall and subjected to engine vibration, but not actually be in the engine compartment. Engineering must evaluate such situations as they arise.

The vibration categories shown in Figure 5.3-1 have been developed in the outline form shown in Table 5.3-1. These vibration categories have been identified for an F-104 and are shown in Figure 5.3-2. It must be noted, however, that equipment locations in an aircraft cannot be selected solely on the basis of shock and vibration considerations, since to do so might alter the aircraft static balance or subject the equipment to excessive environmental extremes.

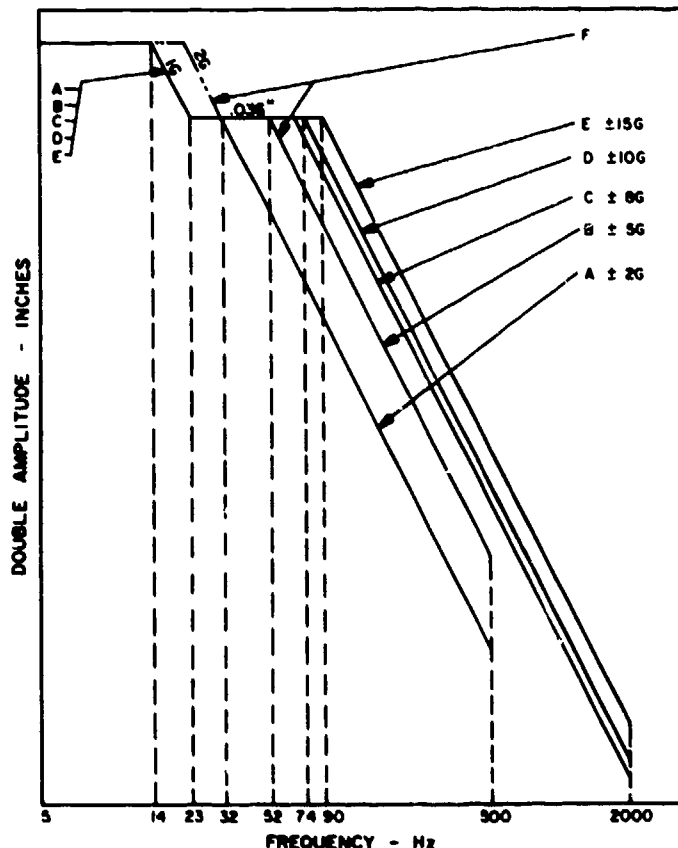


Figure 5.3-1 Vibration Categories
(MIL-E-5400)

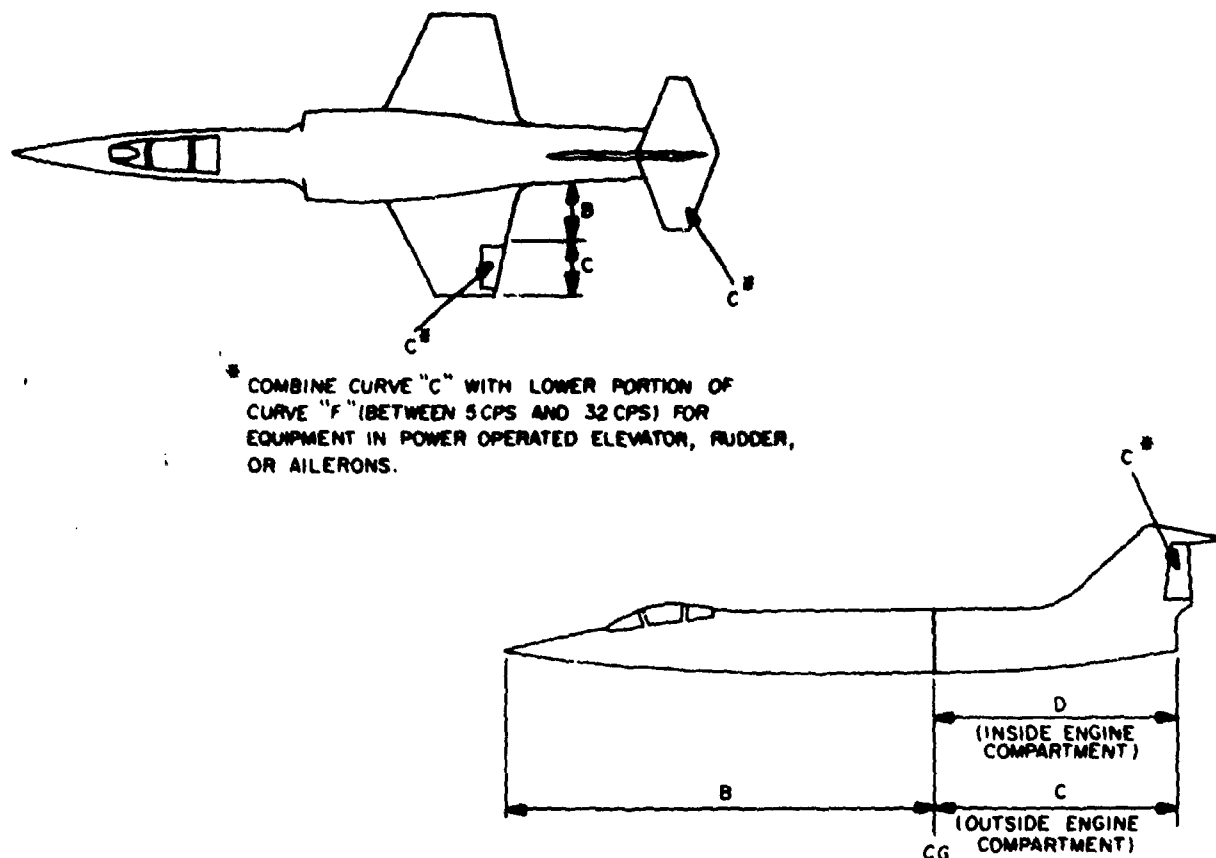


Figure 5.3-2 Vibration Category Locations in a High Performance Aircraft

5.4 Installation Procedures that Minimize EMI

Major efforts in the field of electromagnetic interference control and reduction have usually been concentrated on components, equipments, and, in some cases, entire subsystems. Rightfully so, for these are the areas where most of the problems are found. However, in working out these equipment problems, very little attention is given to the wiring and cabling which interconnects these equipments or subsystems. Little or no information is available concerning such matters, and when it is available, it usually reports on an ingenious scheme which in the end turns out to be a custom installation.

One of the most useful interference control techniques is separation. Unfortunately, this technique is difficult to achieve in an aerospace vehicle. The possibility of maintaining minimum separation distance for all wiring and equipment is seldom possible. For this reason, a comprehensive and systematic method is outlined below to guide the installation of wiring and cabling in closely confined areas. The use of such a method can provide conformity of installation and ultimately result in interference reduction.

5.4.1 Wire Classification and Harnessing

One of the most useful methods for achieving EMI control is based upon the separation of wires and cables into similar classes of power handling and susceptibility levels during their installation.

Mil-W-5088 and MIL-STD-461, Notice 4, classifies wiring into four to six groups in order to maximize isolation between wiring/cabling classifications. The method is only briefly outlined below, since each installation should be considered individually. Refs. (4, 8, 57, 58, 59, 60).

5.4.1.1 Category I Distribution Power Wiring

1. Three phase distribution wiring (115/200 volts ac).
2. Single phase distribution wiring (115 volts ac).
3. Other wiring carrying (115 volts ac).

There are two sources of coupled energy that can cause interference: The magnetic field and the electrostatic field. Of the two, the magnetic field is the most difficult to control, since shielding is basically ineffective. The practical method of magnetic field isolation is physical separation, where the current carrying wires are isolated from other power lines. Motors, relays, most power transformers, actuators, and other power devices are insensitive to induced voltages and transients. Therefore, it is possible to group all distribution power wiring into one category. The primary, or feeder wiring is not grouped with the distribution wiring to minimize damage in the case of fault current.

5.4.1.2 Category II - Secondary Wiring

1. Low voltage power circuits.
2. Low voltage lighting circuits.
3. Synchro and servo circuits not in Category III.
4. Equipment power supply wiring routed to other equipments within the same system for dc voltages up to 5000 volts.

Secondary power wiring is generally classified as wiring carrying power at voltages less than 115 volts, ac/dc. Secondary power wiring can be a problem in confined areas such as cockpits, radio racks, conduit runs and other similar areas of high density wiring. Since the magnetic field is directly related to the current, and since secondary power wiring is often routed with sensitive wire bundles, it is necessary to identify this wiring as a separate category.

5.4.1.3 Category III Control Wiring

1. All instrumentation wiring that involves the operation of relays (the solenoids), stepper switches, intermittent pulsing energy such as cameras, etc.
2. Any basic aircraft wiring that carries pulsed energy caused by system operating characteristics, such as flashing high intensity lights.

The wiring in Category III is identified as wiring that carries transient magnetic or electrostatic fields. Category III is similar to Category II except that it also includes transient energy. If transients do exist but do not affect other systems or wiring associated with safety of flight, then Category III wiring may be changed to Category II.

5.4.1.4 Category IV - Sensitive Wiring

1. All microphone circuits.
2. All audio and video signal circuits.
3. All sensitive control circuits and gain controls.
4. Signal wiring requiring shielding.
5. All meter and bridge type circuits.
6. All computer signal circuits.
7. All demodulator signal circuits.

There are many varieties of wires that make up this category. Most of the wiring in this category is susceptible to electrostatic types of energy because of the high impedance characteristics of these circuits. Low impedance circuits are susceptible to magnetic fields. However, a low impedance circuit can also act as a carrier of electrostatic energy that can conduct spurious energy into a sensitive circuit such as a microphone input into an amplifier. Most of the above wiring is required to be shielded.

5.4.1.5 Category V - Susceptible Wiring

1. All antenna coaxial cables.
2. All wiring to electro-explosive devices (see also Section 7.2)
3. All wiring pertaining to aircraft systems, particularly the flight safety related system and indicators.

Past experience has shown that certain wiring is particularly susceptible to almost all levels of electrical energy. Such wiring shall be routed free of all other categories of wiring and must not be grouped into a bundle unless associated with its own unique system. For example, UHF radio antenna cables may be grouped, provided that individual shielding integrity is good. High power transmitter antenna cables and radar pulse cables, however, should be routed separately.

5.4.1.6 Category VI - System Wiring

This category is a compromise established for the convenience of installation. To minimize extensive analysis of uncertain wiring categories and to reduce the resulting separation requirements, Category VI may contain certain system wiring that otherwise would be placed in Categories II, III, and IV. Categories I and V must not be considered. Category VI system wiring may be created only after careful analysis has shown that the wiring is free of interference. For example, an automatic flight control system (AFCS) has Category V wiring as part of its cabling. These bundles and other AFCS wiring in the immediate area can be grouped and reidentified as Category VI system wiring. It is suggested that each system bundle be identified and routed separately. It is not recommended that Category VI subsystem bundles be mixed or grouped together with other system wiring.

5.4.2 Separation Design Limits

Minimum coupling between wires of various categories can be controlled by specifying the minimum distance between cables to be maintained throughout a cable routing. Table 5.4-1 gives the ideal minimum separation data for physical separation. Unfortunately, these distances cannot usually be maintained in most aircraft because of limited space. Accordingly, compromises must be made.

Table 5.4-1 Ideal Minimum Separation Distances Between Categories
[In centimeters (inches)]

CATEGORY	DESCRIPTION	SEPARATION, cm (in.)
I	Primary Power	30.5 (12)
	Distribution Wiring	15.3 (6)
II	Secondary Wiring	7.6 (3)
III	Control Wiring	7.6 (3)
IV	Sensitive Wiring	7.6 (3)
V	Susceptible Wiring	7.6 (3)
VI	System Wiring	7.6 (3)

Classifying the categories as "transmitters" and "receivers" can help in understanding why the categories are spaced as shown in Table 5.4-1. Further, the comparison will assist in the process of making compromises later on. Categories I, II, and III can be classed as transmitters and Categories IV and V as good broad-band receivers. Category VI however, contains both transmitters and receivers that have been shown as not interfering with each other.

5.4.3 Separation Compromises

Practical considerations for the installation of wiring bundles require some careful modification of both the categories and spacing. There will be areas in the aircraft where the installation of instrumentation wiring will be bundled together or routed too close together. Three examples are noted in the following paragraphs.

5.4.3.1 Lightening Hole Routing

Wire bundles must maintain their spacing until they immediately enter the lightening hole and should break away as soon as possible after passing through. Whenever possible, categories should be grouped and routed as follows: Group categories I, II, and III together and route through the same lightening hole. Route categories IV, V and VI separately whenever possible, although IV and V can be grouped together and routed through the same hole if necessary.

5.4.3.2 Common Connectors

For purposes of routing, connectors are considered to be the same as lightening holes; however, Category IV signal wiring should be separated into input and output wire harnesses and routed through their separate connector. (See Section 5.4.1.4).

5.4.3.3 Conduit Routing

The grouping of wiring categories and their routing through conduit is similar to the grouping use for clamping wire bundles. Their parallel routing distances must be kept to a minimum so as to minimize the interference coupling. Unrestricted use of metallic conduit should be discouraged, since the reflected inner fields for categories IV, V, and VI could increase their mutual coupling, particularly category VI, which is a compromise to some extent in the first place.

5.4.4 Special Wiring

Special wiring includes all types of wiring configurations other than the single-conductor-insulated wire. Special wires are always used for the control of interference and in the wire-category outline, special wires are used for isolation purposes where the physical distances must be reduced for practical reasons. Therefore, the special wiring would replace the single conductor wire under certain installation conditions.

There are two basic types of special wire: twisted wires (two or more) and shielded conductors (one or more). Twisted wires are used for control of radiated or induced magnetic fields, and the shielded wire is used for the containment or exclusion of electrostatic fields. Combinations of both are used where the circuitry may be susceptible to magnetic and electrostatic fields. Configurations recommended for use include the following: twisted pairs, shielded twisted pairs, shielded single conductor, and the various configurations of coaxial cable.

Special wiring is used only when and where necessary if not called out in the system design. Use of special wiring is an admission that the system is susceptible or radiates over some specified portion of the electromagnetic spectrum (just as a gasket is an admission that a perfect mechanical joint cannot be obtained). Requirements for extensive use of special wiring may be reduced by considering the EMI effects prior to the design of the electrical/electronics portion of the system. To avoid ground circuit problems it must be emphasized that all shielded wire must be insulated with an external non-conductive jacket.

One of the penalties incurred by using shielded wiring is its additional weight. This added weight can be minimized if all the Category IV signal wiring is placed within a common shielded jacket; not only does this save weight, but it also minimizes the problems associated with tying individual shields together.

Instrumentation equipment racks are frequently so highly congested that wire separation as shown in Table 5.4-1 is an impossibility. The problem can be resolved by considering each wire as it leaves its connector as a separate case. The wiring can then be grouped into categories at a distribution center or terminal strip. Wire lengths can vary from one-half to three meters (1.5 to 10 feet). Lengths in excess of three meters (10 feet) should be considered for classification into categories. Since space isolation is not possible, the only recourse is to specify the use of special wiring. Power wiring should be twisted with the ground return for wires grouped under Categories I and II. Single and two conductor signal wiring should be shielded (Categories IV and V). In general, the requirements for special wiring to achieve isolation does not exist after the wiring has entered the proper categories.

In referring to Figure 5.4-1, it will be noticed that the categorized wiring has been labeled in a definite order. When using parallel runs (where all of the categories are in the same "plane"), it is desirable to locate the bundles for minimum coupling. The suggested order would be: I, II, III, VI, IV, and V where Category I is always the farthest distance from any terminal board wiring and/or Categories IV and V. Category dedicated modular junction terminals provide optimum isolation.

5.4.5 Ground Wires

Ground wires must take the category of the mating "hot" wire. Twisting of pairs of wires usually refers to the hot wire and the (ground) return. Twisted pairs of wires may be used on circuits of either transmission (Categories I, II, and III) or circuits of reception (Categories IV and V). The former reduces the magnetic field coincident with current flow and the latter inhibits induced magnetic fields. Twisted wires may also be used to reduce the loop aperture where a tight twist results in minimum loop area (see Section 3.4.1.1.2).

5.4.6 Ground Studs

All ground studs will take on the category of the attaching wire. This immediately implies that only one category can be connected to a given ground stud.

5.4.7 Engineering Control

The careful planning that is required to identify wiring categories can be defeated unless proper engineering control is exercised. As shown in Figure 5.4-1, each wire is carefully identified as to its category. This is done specifically for illustrative purposes only. The identification of categories is properly done as a part of the wiring list as shown in Table 6.4-1.

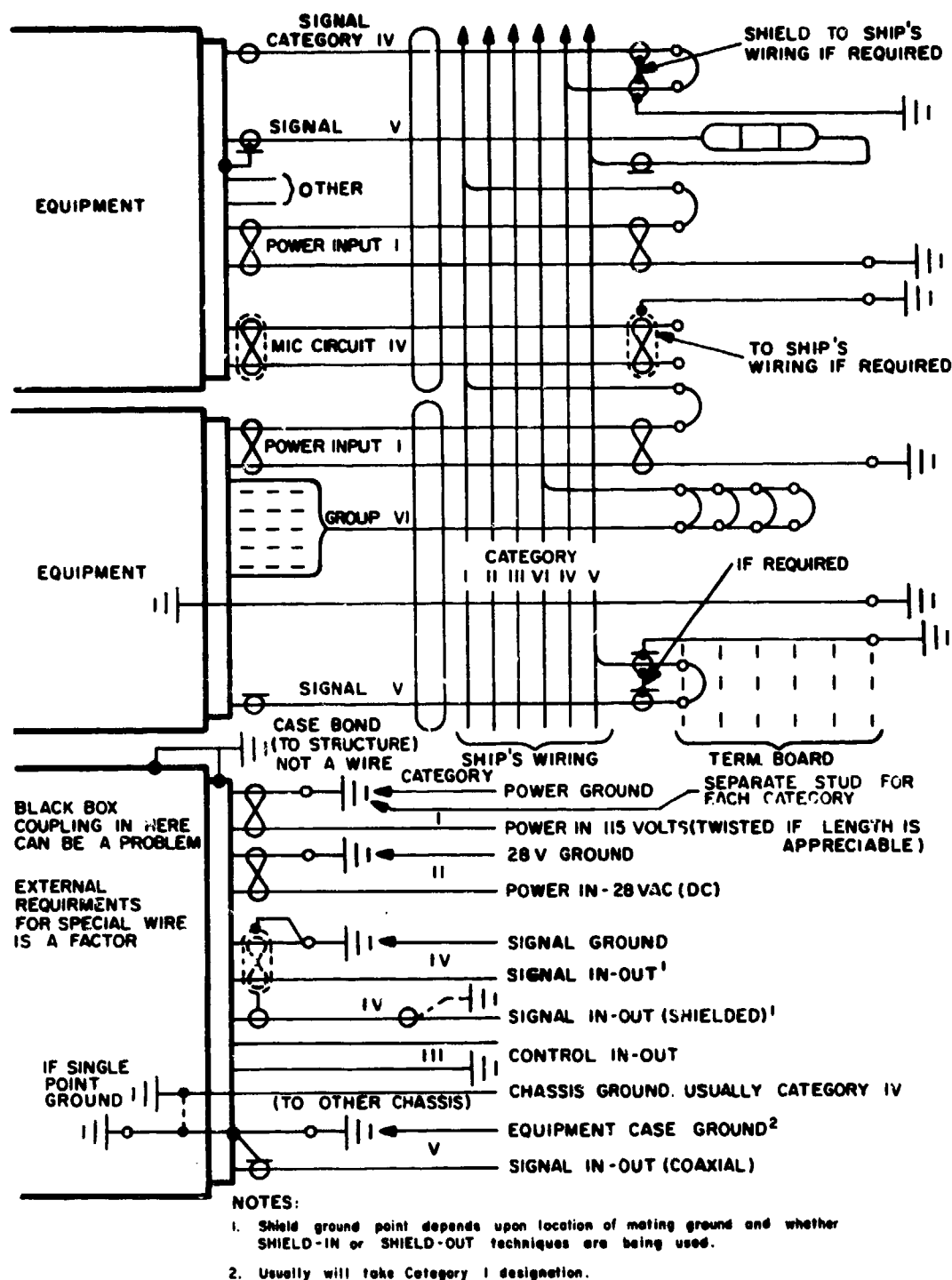


Figure 5.4-1 Category Oriented Schematic Diagram. (Ref 59)

Application of a classification plan to all the instrumentation wiring in the aircraft will result in a considerable reduction of system interferences caused by inadvertent coupling. Wire classification is a distinct aid in the solution and tracking down of many electromagnetic compatibility problems. The classification plan does not conflict with circuit or interconnecting wiring design but is merely a specified installation procedure. The preparation of drawings that assign identification numbers to the wiring are not affected by the wire classification requirements, nor are removals or additions of equipment to an existing installation. Economically, the costs of engineering design are more than offset because of the minimum rework for a given installation design. Wire classification eliminates the wide variances in compatibility found on aircraft that contain a random wiring classification.

5.4.8 Miscellaneous EMI De-Coupling Methods

Although the provisions for magnetic and electric field de-coupling should be included during the design and installation phases, there are problems that may occur later during the flight test program. A few "quick-fixes" for these problems are briefly outlined below.

5.4.8.1 "Zipper Tubing" Cable Shields

Existing installations often present problems that prevent rewiring or redesign. A ready-made "zipper-tube" may be a satisfactory solution for unshielded wire bundles. Ref. (61).

Zipper or slide-fastener shield tubes are available in several sizes from 1.9 centimeters (0.75 inch) to 12.7 centimeters (5.0 inches) in diameter. Intrinsic shield braids include both non-permeable (e.g., tin-plated, copper-wire mesh) and permeable type (e.g., tin-plated, copper-clad, stainless-steel wire mesh). In addition to acting as a Faraday shield, the permeable braids offer shielding to magnetic fields. Figure 5.4-2 shows the EMI characteristics of a one type of "zip-on/zip-off" tubing.

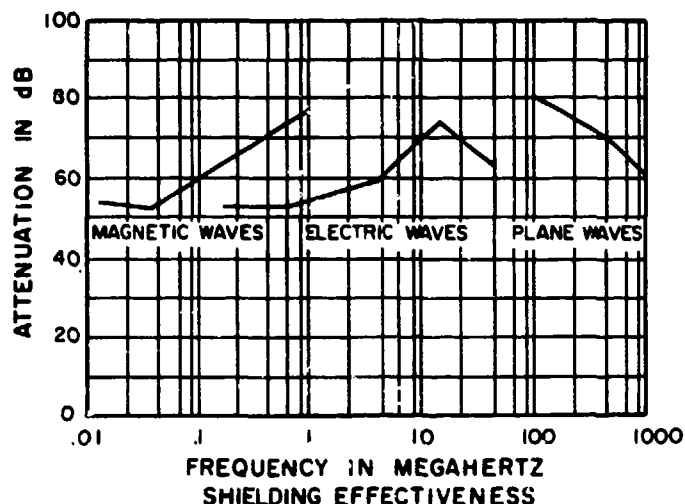


Figure 5.4-2 Shielding Effectiveness of One Type of Zipper Tubing. Ref (61).

5.4.8.2 Mesh-Tape Shields

A useful quick-fix technique for shielding a cable bundle is to use wire mesh tape applied as a wrapping to cover the cable. Typical material is tin-plated, copper-clad steel, knitted to a width of 2.54 centimeters (1 inch) and a thickness of about 15 mils. The permeability of the tape also offers some magnetic field suppression.

Table 5.4-2 Group I is representative of a tin-coated copper clad steel, double wire mesh with about 50% air space, and an equivalent permeability of about 300. Wrapping and advancing the wrap at one half layer per turn results in the low frequency ($f < 10\text{ KHz}$) shielding effectiveness for the different radii shown.

Table 5.4-2 Low Frequency ($f < 10\text{ KHz}$) Magnetic Shielding Effectiveness of Types. Ref. (B5).

GROUP	MAGNETIC TAPE (Foil)	RADIUS OF WIRE HARNESS, cm (in.)		
		r=0.254 (0.1)	r=0.635 (0.25)	r=2.54 (1.0)
I	Technit Magnetic Tape	30 dB	21 dB	16 dB
	Metic, 0.01016 cm Tape (0.004 in.)	32 dB	24 dB	18 dB
II	Co-Netic, 0.01016 cm Tape (0.004 in.)	45 dB	37 dB	31 dB
	Co-Netic, 0.0254 cm Tape (0.010 in.)	52 dB	44 dB	38 dB

5.4.8.3 Metal Foil Tapes

Still another tape available is the solid flexible metal tape. This method is inexpensive and quick; however, it may be difficult to retain the "solid" wrapped covering if the cable bundle is often flexed during use. Some tapes are made with a conductive adhesive to improve the continuity of wrapping when the bundle is flexed. It is vitally important to maintain complete coverage during wrapping, since air gaps will reduce the magnetic shield effectiveness. Table 5.4-2 Group II contains examples of solid foil tapes.

Magnetic foil tapes are available in thicknesses that vary from two mils to ten mils, and width variations from 1.27 centimeters (0.5 inch) to 5.08 centimeters (2 inches). A minimum foil overlap of 50% is suggested in order to maintain the adhesive bonding. Double wrapping is also suggested in cases when flexing will occur.

5.4.8.4 Conductive Heat Shrinkable Tubing

This type of heat-shrinkable tubing is made of a material whose inside or outside surface is electrically conductive. The conductive coating is usually a silver deposit which remains intact and conductive after shrinking.

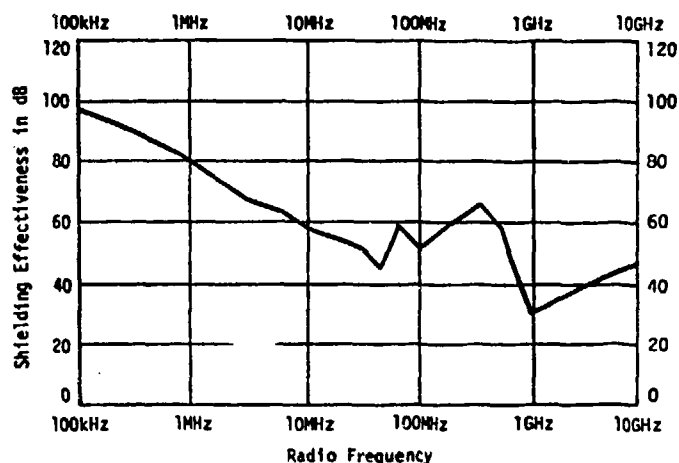


Figure 5.4-3 Electric-field Shielding Effectiveness of Heat-Shrinkable Boots. Ref. (B5)

Special connector boots are available that provide EMI shielding, shield grounding, and strain relief in the termination of connector backshells. Typical attenuation characteristics of conductive coated heat shrinkable boots provide in excess of 30dB of attenuation in electrical fields at 1 GHz to nearly 100dB at 100 KHz as shown in Figure 5.4-3.

5.4.8.5 Ferrite Beads and Rods

A special type of EMI quick-fix is the ferrite bead and rod. Smaller than a pencil eraser, one or more of these beads or rods may be slipped over individual wires coming from a common power supply or other system suspected of conducting EMI or RF transients. It is important to note that they are ineffective below 10 MHz and are usually limited to about 5 amperes of dc or 400 Hz power sources.

When the ferrite bead or rod is slipped over a wire, the magnetic-field intensity concentrates in the lower reluctance path of the bead or rod rather than the surrounding air. Figure 5.4-4 depicts the attenuation characteristics of the ferrite bead.

5.5 EMI Control During Installation and Maintenance of Crew Area Switches and Displays

Design objectives for instrumentation controls and displays in the cockpit must include features for installation and maintenance. Installation/removal must be straightforward and accomplished without removal of other panels or hardware. Dedicated cable(s) must provide sufficient length to provide display removal/installation. Adequate mechanical protection of the electronics located on the back side of the panel should be provided; this can take the form of a complete housing or "bumper bars".

Maintenance relates to the ability to ensure serviceable operation of equipment. Careful design and parts layout will be a distinct advantage during trouble-shooting and parts replacement. Standard, well-identified components are a necessity. Up-to-date schematics are invaluable.

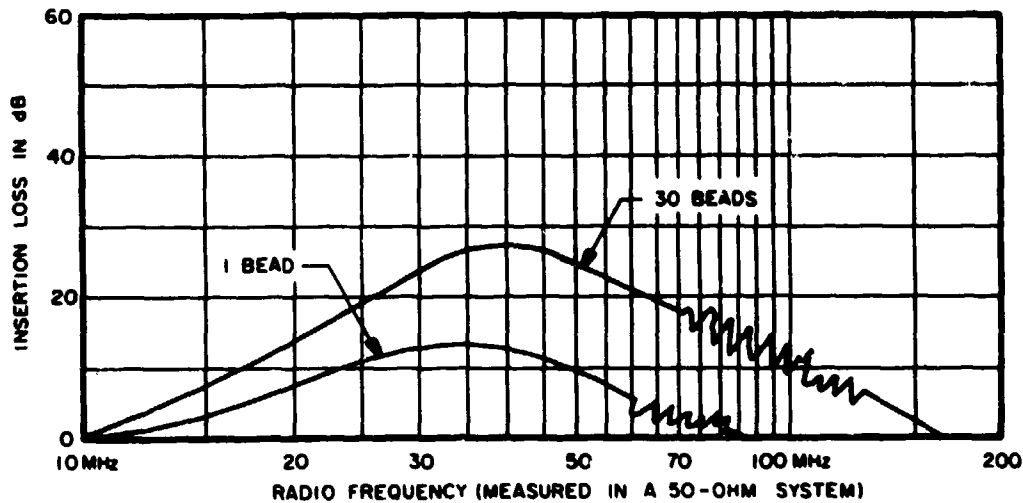


Figure 5.4-4 Comparison of Attenuations of Ferrite Beads
Ref. (B5).

5.5.1 Design Guidelines

Although the basic design for most display and control panels are engineered by groups proficient in such design, it sometimes is necessary for the instrumentation engineer to design auxiliary panels. The following list suggests a few fundamental requirements.

1. Displays and controls that are susceptible to damage or to inadvertent activation as a result of normal pilot/crew operations shall be appropriately guarded.
2. Time-shared displays should be used whenever continuous monitoring is not required. This approach conserves panel space and improves grouping.
3. Fixed scale, moving pointer meters are generally preferred.
4. Scale graduations generally preferred progress by one, five, or two units, in that order.
5. Avoid non-linear scaling.
6. Flight control and navigation displays should use "fly-to" pointers.
7. When operations follow a sequence or logical pattern, group the controls/displays accordingly.

The control devices used on most panels consist of toggle switches, pushbutton switches, rotary switches and circuit breakers.

5.5.2 Special Installation Requirements

Attenuation offered by shielding materials to electric, magnetic, and electromagnetic waves are achieved in a theoretical manner. In actual practice, however, this attenuation is compromised and not easily realized. Nearly all instrumentation systems have penetration areas. For example:

1. Cover plates and access covers.
2. Meter windows.
3. Digital or display windows.
4. Shaft extensions (potentiometer).
5. Cooling vents.
6. Switches.
7. Fuses, cartridge type.
8. Indicator lamps.
9. Signal shields not fully insulated.

10. Power and signal leads.

11. Connectors.

5.5.3 Typical EMI Installation Problems and Solutions

Leakage or penetration through designed "holes" are typical of control panels, display panels, and ground test equipment. These penetrated areas result in shielding discontinuities and ultimately degrade EMI immunity. Generally, these problems occur through design oversight rather than inadequate methods or procedures to control them. A few typical problems and their solutions are suggested in the following examples. Refs. (57, 60).

- 1 Problem- Cover plates and access holes.

Solution - Properly installed EMI/RFI gaskets which allow a pressure-tight fit.

2. Problem - Meter and Display Windows.

Solution - Electroformed mesh of 100 lines per inch will provide a light transmissibility in excess of 80% and adequate EMI attenuation. Various types of this mesh are available and can be attached to the window or sandwiched between two windows.

3. Problem - Rotary switch shafts extending through panel usually are poorly bonded.

Solution - A cup or spring washer is inserted over the shaft under the knob. Pressure is exerted by the knob thus providing a low resistance path. (Figure 5.5-1).

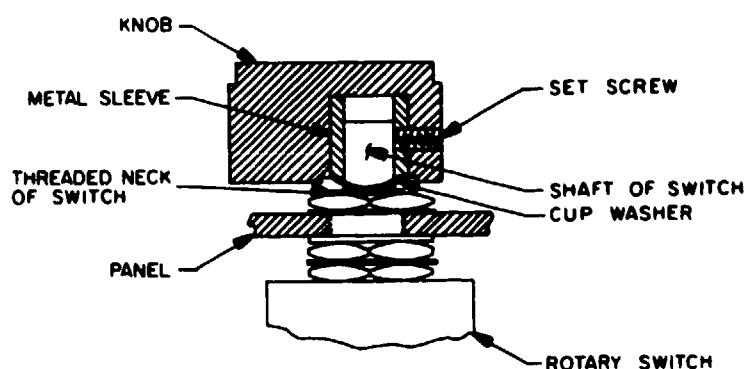


Figure 5.5-1 Rotary Switch - Spring Washer Bonding. Ref. (57).

4. Problem - Push button switches can generate interference through switch assembly contacts and radiate this noise through the actuator shaft.

Solution - The switch can be shielded by a conductive "boot" and conductive housing covering the switch body.

5. Problem - Fuse cartridges exposed to noisy environment.

Solution - Fuse holder with fuse can be mounted within grounded box.

6. Problem - Panel or indicator lamps designed with a press-to-test feature.

Solution - A procedure similar to panel meter EMI control is used. Provide a mesh screen to cover the lens of the light assembly. Be sure to provide proper grounding through assembly to chassis panel.

7. Problem - Interference generated by toggle switch can be radiated through switch assembly by the toggle switch handle.

Solution - Add a grounding clip to the handle (see Figure 5.5-2) and ensure that the switch assembly is grounded to the panel.

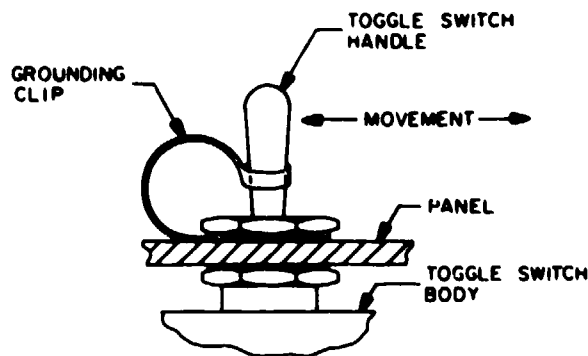


Figure 5.5-2 Toggle Switch Grounding Clip. Ref. (57)

8. Problem - Elusive common mode noise.

Solution - A check of the insulation which covers the shield may reveal an area where chafing or accidental damage has allowed the shield to be accidentally grounded.

5.6 Transducer Installation Considerations

The installation of an instrumentation sensor on or in the test aircraft warrants careful attention and careful follow-up to insure that all personnel involved with the installation understand the sensor's purpose. The importance of follow-up is best illustrated by the following examples:

5.6.1 Microphone Installation

A series of 0.635 centimeters (0.25 inch) and 1.27 centimeters (0.5 inch) microphones were installed with their diaphragm flush with the aircraft skin to measure boundary layer noise. The system was satisfactorily checked out, and Quality Assurance was asked to approve the installation. Shortly thereafter, the aircraft was ferried to the flight test area and readied for flight. Final tests were made of the microphone system, and the results indicated that one microphone had failed and at least three others had shifted in their response. The microphone diaphragms were checked for damage, and the problem was readily apparent. Quality Assurance had stamped each diaphragm as A-OK and ready for flight. A brief investigation revealed that the installation and engineering checkout were satisfactorily made at location "A" but the inspection of the microphone installation was carried as an open item in the aircraft log book to location "B." Upon arrival at location "B" a mechanical inspector had cleared the item and stamped each diaphragm as "OK" for flight, inadvertently causing the damage.

The problem of follow-up is readily apparent in this example but the solution is rather complex. In general, it is difficult to monitor the exact times of an aircraft ferry flight. It can be assumed that it will occur during first-shift operations and further assumed that second-shift personnel will "work off" open items. Without proper notation in the aircraft's log book, accidents such as the one described are very likely to happen.

Sensitive and unique transducers such as microphones are always prone to mishandling by ground crews not familiar with transducers of this nature. Deliberate and knowledgeable supervision is a must if these transducers are to be properly protected.

5.6.2 Pressure Tubing Contaminants

A variety of flexible low pressure tubing specifically designed for high temperature has been used repeatedly with electromechanical pressure recorders. The clock-type mechanism inside the recorder is very delicate, and proper operation is dependent on keeping the mechanism clean. The high-temperature flex tubing mentioned above is manufactured to very high standards, and under most operating conditions it would not cause a problem. However, using this type of tubing did cause the interim clock mechanism to operate in a less than satisfactory manner. The problem was caused by a few very fine "hairs" which impeded the motion of the clock mechanism. The source of these hairs was the real problem. Where did they originate? The answer was the high-temperature flex tubing! An examination of the tubing surface under a 10 power lens revealed the tubing material to be rather generously compounded of very fine Fiberglas "hairs." A review of previous failures in the subject recorders indicated similar symptoms. The problem had always been solved by thorough recorder cleaning, since all symptoms indicated "stiction" in the clock mechanism. This type of tubing was later replaced in all aircraft using this type instrument. Needless to say, the cleaning rate of the recorders diminished considerably.

Although this problem occurred several years ago, a similar type of tubing is still marketed today. Flexible high-temperature tubing of almost any composition creates a problem when used with instrumentation systems requiring very clean operating conditions. For example, all tubing lengths must be carefully flushed out prior to use to eliminate foreign material trapped inside during the manufacturing process. Further, this flushing process must take place after the flex tubing is cut to length, because most materials generate residue during the cutting process. This residue can very easily be "trapped" within the tubing.

5.6.3 Nose Boom Transducers

The flow vane and static orifices should be installed at least one fuselage diameter ahead of the nose. The mount for the boom should be rigid enough to minimize deflection, due to acceleration and loads effects. Special care must be taken to align the longitudinal axis of the boom so that flow vane "struts" are accurately parallel to the airplane Y and Z axes. The sideslip vane (normally the vane closer to the nose) must project vertically downward. Adequate guards must be provided to protect these vanes from physical damage during the hangar-ground intervals. Ref. (62).

The effects of boom bending due to acceleration and airloads, upwash due to the boom and airplane, and cross flow components resulting from pitching or yawing rates will introduce errors in the measured flow angles as compared to the actual airplane angle of attack and sideslip. The magnitude of each effect must be investigated for each particular installation.

The advantages of the nose-boom pitot-static tube are:

1. Small increasing position error with increasing Mach number, compared to fuselage static system.
2. Insensitive in indicated ambient-pressure readings for angles of attack from 0° to $+12^\circ$.
3. Accurate measurement of stagnation pressure between angles of attack of -13° to $+32^\circ$.

The disadvantages of the nose-boom pitot-static tube are:

1. A long, slender boom presents aerodynamic heating problems at Mach numbers above about 3.
2. Ambient-pressure errors increase at angles of attack larger than $+12^\circ$.

The advantages of the hypersonic flow-direction sensor and fuselage static system are:

1. Stagnation pressure can be sensed accurately over large angle-of-attack (-20° to $+40^\circ$) and angle-of-sideslip ($\pm 20^\circ$) ranges.
2. High temperatures at Mach numbers greater than 3 can be withstood.

The disadvantages of the hypersonic flow-direction sensor and fuselage static system are:

1. Risk of the servosystem failure during flight.
2. Large position error and sensitivity to variations in angles of attack.

5.6.4 Strain Gages

A discussion of aircraft sensors is not complete without a few comments and observations related to installation factors which contribute to strain gage error and/or strain gage failure. Refs. (B9, 63)

1. **Excitation Voltage.** - An output uncertainty of 1% will contribute to an error of 1% of reading.
2. **Lead Wire Resistance.** - Take into consideration length and gage of wire runs, fuses, and connectors as well as temperature environmental effects on wire resistance. Consider using remote sensing of excitation power and constant current gage excitation sources.
3. **Gage Resistance**

During the installation design consider using a 3-wire system to compensate for lead wire resistance variations when only one gage is used. This technique is effective to about 320°C (600°F).

4. Completion Resistors and Temperature Change.

Any change in the bridge completion resistance can cause a zero shift error that appears as strain. The error is dependent on the amount of temperature change and the variation in the change of the completion resistor due to the same temperature change. These completion resistors are usually installed in signal conditioning boxes where the temperature change is small. When they are installed in this manner the resistors are usually of small size and low power ratings; thus, self-heating is the prime contributor to drifts due to temperature.

As useful guideline, bridge completion resistors should be rated for at least ten times the power dissipation calculated by design. Precision wire wound resistors, which are more stable than carbon resistors, should always be used for completion, balance, and shunt calibrate circuitry.

5. Strain Gages and Temperature

Strain gages drift with temperature, but this drift can be minimized by using temperature compensated strain gages.

6. Test Variations

It is of primary importance to be aware of and limit variations in the lead wire lengths used in bench calibrations, loads calibration, and flight loads measurements.

7. Strain Gage Lead Wires

When connecting to the two lead wires of a strain gage bridge it is important to prevent stretching of the wires. The errors created by the change in resistance are often secondary, however, since the lead wires usually separate.

8. Connectors and their associated wiring are the major problem in getting a strain gage circuit to properly operate.

Review the following when a related problem is suspected:

- 1) Proper contact crimping at connectors.
- 2) Thermal EMF's created by bulkhead divisions, chassis walls, and potted "glands".
- 3) Connector contact corrosion.
- 4) Connector vibration during flight; loose connectors or wrong gage contacts.
- 5) Installation wiring errors.

9. Strain Gages Installed in Electromagnetic Fields

Inductive pick-up in the presence of high level electromagnetic fields can be significantly reduced by bonding together two identical foil gages. The two gages are bonded one on top of the other so that the grids coincide in the plan view. The tabs are cut off as shown in Figure 5.6-1 to accommodate the wiring connections. The foil grids should be very closely bonded together to minimize inductive coupling.

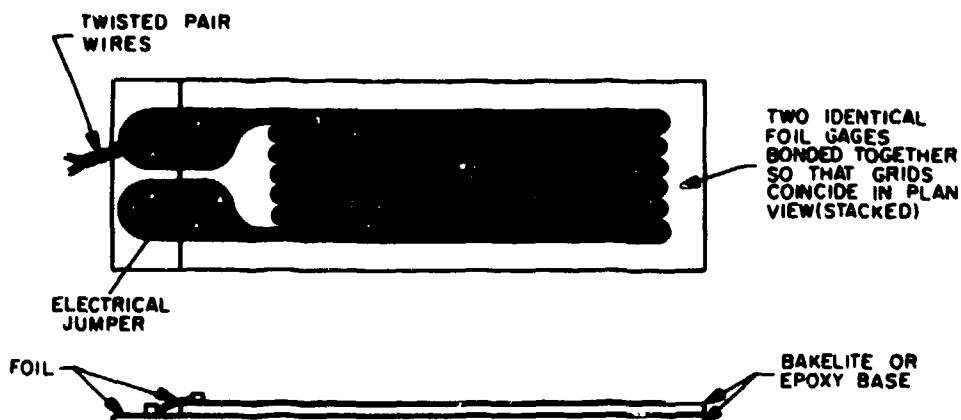


Figure 5.6-1 Back-to-Back Foil Gages

6.0 INSTRUMENTATION SYSTEM VERIFICATION DOCUMENTATION

One of the most important aids to guaranteeing high quality test results is the preparation of effective system verification documentation. Well-formulated verification procedures and related documentation not only aid in coordination of requirements, but also serve as an effective method in guaranteeing the validity of the instrumentation system operation. Complete and well written documentation can help ensure that: Ref. (B10)

- a. All system performance requirements are verified.
- b. Valid performance criteria have been established.
- c. All requirements, facilities, personnel and communications links are identified and their support justified.
- d. Test methods, procedures, and test equipment have been reviewed.
- e. Methods for collecting the testing output and analyzing the results have been clearly defined and established prior to the start of the testing.
- f. Valid measurement techniques and their expected results against which actual inputs and results are compared have been established.
- g. Systems and/or subsystem problems have been identified and their solutions formulated.

6.1 System Verification and Calibration Procedures

If necessary, provide step-by-step calibration procedures to demonstrate that the instrumentation operates correctly and with the proper outputs. These procedures can be broken down into three test phases:

Phase 1 - Develop installation inspection and pre-energizing procedures that will assist in ensuring safety of flight. A typical checklist should verify that:

- (a) All units of equipment have been installed and that their location and orientation are proper. All cables, cooling provisions, transmission lines, etc., have been installed in accordance with the appropriate plans and specifications. Further, that continuity exists for all equipment interconnections.
- (b) The applicable test equipment is available, operationally satisfactory, and properly calibrated.
- (c) All authorized changes, modifications, and alterations have been completed.
- (d) Adequate access has been provided to all equipments for purposes of maintenance.
- (e) All moving devices are free and clear of obstruction.
- (f) All pre-energizing procedures have been accomplished.

Phase 2 - Verify that initial turn-on or exercise of the system and its preliminary testing include step-by-step procedures. The procedures should provide for testing the equipment electrical supply circuits, including all power distribution panels, switches, circuit breakers, and interlocks. Include unique procedures for testing the torquing of connectors, for proper installation of RF transmission lines and waveguides, loading and focusing of cameras, and other special operations.

Phase 3 - Make certain that the installation calibration includes complete instructions for calibrating the instrumentation transducers. The test results must verify that all instrumentation transducers are operationally within calibrated tolerance. When it is required that alignment be accomplished prior to performing the calibration, the alignment should be included or, if too lengthy, a suitable reference to its identification and purpose should be made.

6.2 Instrumentation System Calibration

To insure that the accuracy capabilities of the instrumentation installation is satisfactory, it will be necessary to calibrate the system. This procedure enhances the probability of finding and defining gross inaccuracies and malfunctions soon after they occur. This procedure further implies that some method of in-flight calibration capability is provided.

In general it is not possible to perform a complete system calibration using primary calibration standards. This would require the use of primary standards for pressure, temperature, acceleration, flow rates, etc. for each measure-

ment. On occasion a pressure transducer input can be uncoupled from its system and a secondary standard of pressure substituted for the pressure source; however, it is usually inconvenient or impossible to do with the other measurement types.

Since it is impractical to use primary calibrations standards for all transducer calibrations, a method of voltage substitution is often used. The procedure is as follows: The transducer (and its amplifier if one is used) is calibrated in the laboratory using a primary calibration standard with matched impedances. The result is a tabulation of output voltages from the transducer (and amplifier) versus input to the transducer from the primary calibration standard. These tabulated values can then be plotted, producing a continuous calibration curve for the pressure region of interest. The output voltage values can now be substituted for pressure changes at the transducer. The instrumentation system is calibrated by applying a known voltage at the point where the output of the transducer (or amplifier) would normally be. The system output is then recorded or telemetered to a ground station recorder. Typical calibration curves are shown in Figure 6.2-1. The dotted line correlates the substitution of pressure with voltage output.

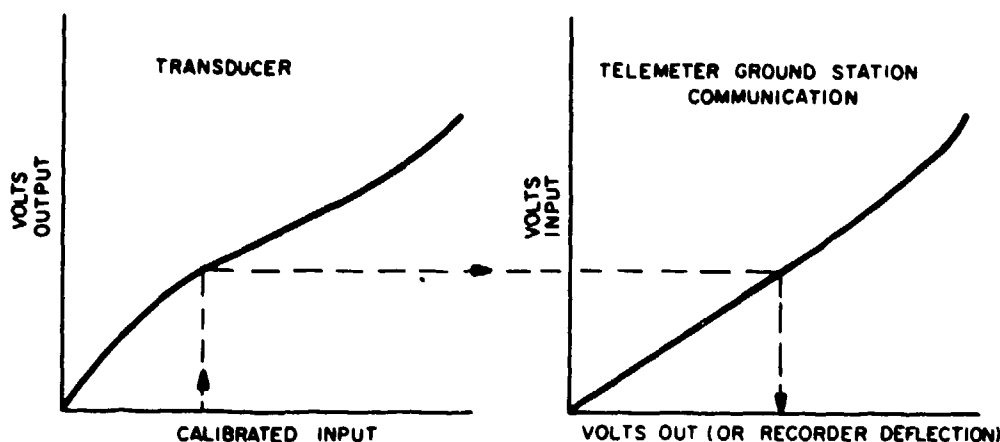


Figure 6.2-1 System Calibration Curves Showing Voltage Substitution.

This method of voltage substitution requires that the transducer-amplifier combination be calibrated as a unit so as to eliminate inaccuracies due to differences in each individual transducer and amplifier.

6.3 Review Boards

The broad requirements for documentation apply to all project review meetings of which the instrumentation engineer is a vital part. The technical state of the design at the time of the review usually determines the extent of the detail required. The review board structure as used by the NASA Dryden Flight Research Center is shown here as an example. The criteria for appointing a review board normally consist of:

- a. Significant new program or operation.
- b. Critical configuration changes or modifications.
- c. Proof-of-concept demonstration or tests.
- d. Hazardous or critical flight test.
- e. Use of specialized equipment or facilities.

6.3.1 Design Engineering Review (DER)

The DER is a function normally established whenever system design is sufficiently developed and identified so that a credible review and assessment can be made. The DER performs design evaluations prior to an installation, and may continue through the installation phase so long as design/engineering changes may be required. The DER will normally conclude with the establishment of an Operational Readiness Review, if applicable.

6.3.2 Operational Readiness Review (ORR)

The ORR precedes the first flight or specified operation at a time when credible review and assessment can be made without delaying the operational schedule. The ORR may be a follow-on function to the Design Engineering Review, or may be established as an independent evaluation of individual or combined operations associated with any type of flight or ground activity.

6.3.3 Board Functions

The functions of the Board should include the following as appropriate for the type of review (DER or ORR) being conducted:

a. Both Boards (DER and ORR)

- (1) Conduct an independent review and assessment of the total program or operation and assure that adequate and proper planning and preparation is accomplished to result in meeting required objectives under acceptable safety conditions. A major goal is the development of current and correct operating instructions, effective configuration control and positive safety and quality procedures.
- (2) Provide engineering and technical recommendations to concerned personnel, while recognizing that it is not a function of the Board to request or direct the actual work effort.
- (3) Maintain effective communication among Board members, program/operation personnel, and the Program Manager or his representative.
- (4) Submit a formal report of Board activity, findings, and recommendations to the Program Manager or his representative, with copies to the Safety and Quality Assurance Office. Submittal of this report must be early enough in the schedule to allow for timely and effective action as required.

b. Design Engineering Review Board

Objectively review and assess all facets of the program, including as applicable:

- program objectives and general plan
- design philosophy and application
- development activity
- engineering approach
- system safety (hazard analysis and risk assessment)
- preliminary test planning
- preliminary operational planning

c. Operational Readiness Review Board

Objectively review and assess the state of readiness of the installation verifying that it has met the safety provisions, including, as applicable, proper establishment, definition, and implementation of the following:

- operational objectives
- operational planning and methods
- emergency/contingency planning
- system safety (hazard analysis and risk assessment)

6.3.4 Responsibilities and Procedures

The following actions are generally applicable to the performance of Design Engineering Reviews and Operational Readiness Reviews, although not necessarily in the exact order shown. Specific actions will vary according to the type, size, and complexity of the program or operation.

a. Appointing Memorandum - The Program Manager or his representative should appoint the Board by means of a memorandum to concerned personnel which:

- (1) Identifies the Board members, Board chairman, and advisory or consultant personnel where applicable.
- (2) Identifies the program or operation concerned.
- (3) Identifies the purpose of the Board and any specific areas of concern or desired special effort.

- (4) Establishes meeting places and times and specific reporting requirements; however, these are normally established by the Board chairman.
- b. Board Briefings - Required briefings should be presented by qualified program or operation personnel to familiarize the Board with the overall effort, and the specifics of all areas under evaluation. It is the responsibility of program/operation personnel to assure that all information provided to the Board is current, complete, and accurate; that all hardware and equipment submitted for evaluation is properly prepared and represents the actual configuration and functional characteristics intended for use; and that all known or suspected anomalies, deficiencies, discrepant conditions, and areas of concern or question are identified.
- c. Evaluations - The Board should perform required and appropriate evaluations of the concerned program or operation, including, as applicable, the design, fabrication and performance of hardware, and the correctness and adequacy of software.
- d. Board Report - After completion of all actions considered necessary by the Board to properly accomplish its appointed purpose, a report signed by all Board members shall be submitted to the Program Manager or his representative. No specific report format is required, but the Board determinations, recommendations, and conclusions provided in the report shall be based on information acquired and evaluated as described in b. and c. above. The report shall include:
 - (1) A review of all chronological/historical Board activity.
 - (2) Recommendations regarding the concerned program or operation, specifically including all areas of concern and proposed changes, restrictions, and limitations.
 - (3) Specific identification of all non-concurrences by any Board member.
 - (4) Supplements and attachments pertinent to the report.

Individual Board members have the right of dissent with any action or recommendation of the overall Board membership, and such dissent, if not subsequently resolved, shall be a matter of record on all pertinent documentation, including the Board report. The report must be signed by the chairman and all members of the Board prior to submittal to the Program Manager or his representative. The signature of any member does not necessarily indicate that he agrees with all portions of the report, but does signify that he has reviewed the report, that in his opinion it is complete and factual, and that his areas of disagreement or nonconurrence are properly presented.

6.3.5 Operational Readiness Review Checklist

An operational readiness review checklist may be used by concerned operational/support personnel and the ORR Board as an aid in determining that specific requirements have been considered and are properly complied with or are not applicable to the operation.

Operational Readiness Review (ORR) Checklist Technical

1. Are operational objectives and proposed methods of accomplishment (technical approach) clearly defined and compatible?
2. Have technical support requirements been coordinated with concerned elements to ensure performance and avoid schedule conflicts?
3. Are sufficient qualified personnel being utilized?
4. Is there a requirement for training, simulation, dry run?
5. Are proposed facilities and equipment adequate?
6. Are special techniques or processes required? Are they provided for?
7. Is the planned gathering/recording of operational and safety-critical data adequate?
8. Are specific vehicle/equipment limits clearly defined and understood?
9. Is there an above-normal possibility that limits will be exceeded?

10. Has prior experience with similar operations, and qualification and other test data, been reviewed and utilized if appropriate?
11. Is the performance of the operation correctly specified in approved documentation (drawings, specifications, manuals, procedures, etc.)?
12. Is additional technical information required?

Safety

1. Is the planned sequence of operations logical and satisfactory from a safety viewpoint?
2. Are hazards identified and criticality determined?
3. Is there any undue hazard to personnel, or possibility of damage to equipment?
4. Have hazards been eliminated? If not, are they controlled by safety devices, warnings, procedures, etc.?
5. Has identification been made of conditions having a high risk potential which cannot be minimized, including their relationship to program goals, scheduling, facilities, other programs?
6. Can the operation be accomplished easier and safer by other methods?
7. Is the established operational envelope being exceeded?
8. If the envelope is being exceeded, is it authorized, are necessary precautions being taken, and are required controls established?
9. Have necessary emergency procedures been established and documented?
10. Are GO-NO-GO criteria established and documented?
11. Is the GO-NO-GO decision-maker identified?
12. Is the overall operation acceptable to engineering, operations, support elements, safety/quality?

6.4 Record Keeping and Documentation

The process of developing an instrumentation installation requires a variety of decisions and a careful accounting of each item of hardware and wiring contact assignment. The instrumentation engineer should devise a method of recording these decisions and assignments.

Since signal wiring and associated connectors constitute the bulk of installation hardware, an accounting of connector and contact assignments will be the most useful.

6.4.1 Wire Lists

A carefully assembled wire list can serve both the instrumentation engineer and the technician. During the development of the wiring diagram, as each wire or cable is added to the diagram it is assigned a wire number or code. A careful accounting of assigned number, wire size, and routing per each wire contact assignment must be recorded. Such a record is often referred to as a wiring list.

A wire list can be very simple or highly complex. A very simple list consists only of the numbers used to identify each wire. This is a minimum requirement assuring that numbers will be used only once.

Table 6.4-1 A Detailed Wiring List

Wire Number	Gage	EMI Class	Segments	Color and Number of Conductors	Routing Disconnects	Drawing Page
642	22	IV	A - B	(Bk,W,R,Gn), 4C	D6	4.8
643	↑	↑	↑	↑	↑	↑
644	↑	↑	↑	↑	↑	↑
645	↑	↑	↑	↑	↑	↑
646	↑	↑	↑	↑	↑	↑
647	↑	↑	↑	↑	↑	↑
648	↑	↑	↑	↑	↑	↑
649	↑	↑	↑	↑	↑	↑
650	↑	↑	↑	↑	↑	↑
651	22	IV	A - B	(Bk,W,R,Gn), 4C	D6	4.8

The wire list shown in Table 6.4-1 has been derived in part from the wiring diagram shown in Figure 6.4-1. In contrast to the simple list of wire numbers, this wire list is more complex and represents considerable time and effort. The columns provide the following information.

- The assigned wire number. Shown here are Wire Numbers 642-651.
- The wire gage identifies the wire size and thus its current carrying capacity.
- The EMI Class identifies the wire as either a receiver or transmitter of interference. Class IV is a receiver.
- The segments A and B indicate that the wire/cable passes through a disconnect of some type.
- The color and total number of conductors in the cable must be listed. Shown here is a four conductor cable (4C) with the colors Black, White, Red, and Green. Parentheses around the colors are used to indicate a shielded cable.
- The cable routing is shown by listing the disconnect/s through which the cable is routed.
- Listing the drawing page number facilitates locating the wire or cable listed.

The complex wiring list as initially prepared appears to contain information readily found elsewhere in the diagrams. However, the advantage of this type of listing becomes evident months or even years later, when wiring changes, equipment changes, and even project assignment changes interrupt the initial and carefully planned wiring diagram design efforts. An up-to-date wire listing such as the example shown will help maintain control over the wiring installation.

6.4.2 Connector Lists

The interface with wire number assignments is connector contact assignments. Refer to Figure 6.4-1. The aft instrumentation compartment disconnect is carefully documented. Each contact assignment must be recorded as it is used. Figure 6.4-1 illustrates a method often used to account for each contact in a connector. This diagram is required for the routing of each wire, and the tabulated data form shown in Table 6.4-2 is derived from the wiring diagram after final routing and installation.

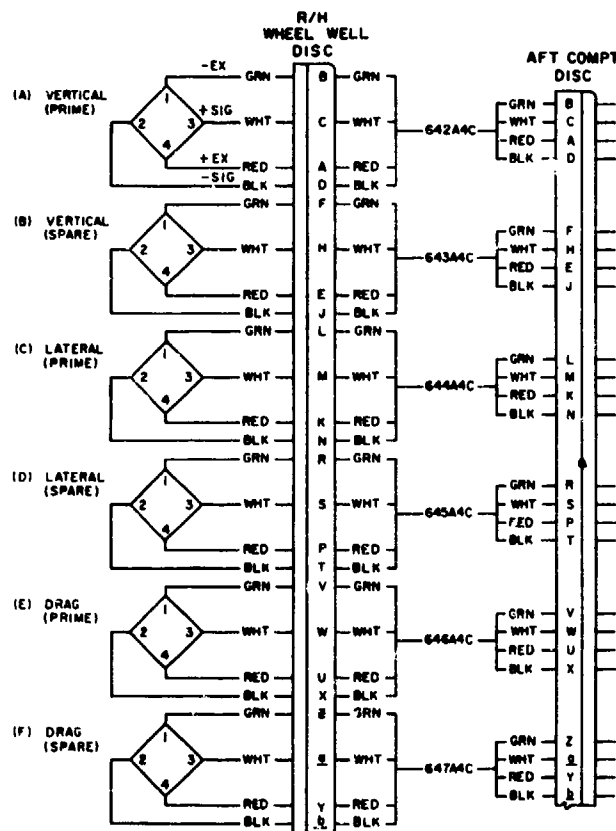


Figure 6.4-1 Aft Compartment Disconnect.

Regardless of the method used, the connector contact assignments must be carefully controlled, particularly when two or more categories of wiring are routed through the same connector. (See Section 5.4.1). In these circumstances, each category must be routed together by grouping contact assignments. This is a good reason for not "scattering" the contact assignments when using a connector of large contact capacity.

Table 6.4-2 Tabulated Connector Assignments.
Compare with Figure 6.4-1, Aft Instrumentation
Disconnect.

P		MRAC104		J	
Drawing Page	Wire Identity	Contact	Wire Identity	Parameter	
4.8	642A4C	Bk W R Gn	D C A B	Bk W R Gn	Vertical (prime)
4.8	643A4C	Bk W R Gn	J H E F	Bk W R Gn	Veritcal (spare)
4.8	644A4C	Bk W R Gn	N M K L	Bk W R Gn	Lateral (prime)
4.8	645A4C	Bk W R Gn	T S P R	Bk W R Gn	Lateral (spare)
4.8	646A4C	Bk W R Gn	X W U V	Bk W R Gn	Drag (prime)
4.8	647A4C	Bk W R Gn	b a Y Z	Bk W R Gn	Drag (spare)

6.4.3 Other Examples of Record Keeping

Until now, the discussion has primarily been directed at the equipment connectors and their wiring. Additional record keeping is required for the following, for example:

1. Tape recorders - parameter/recorder channel assignments.
2. Commutator - parameter/input channel assignments.
3. Signal conditioning boxes - parameter/input/output assignments.
4. Time code generator.

Items 1 through 4 are usually added to the wiring diagram within the "box" drawn to represent the chassis that is being wired into the instrumentation system. Examples of each are shown in Figure 6.4-3.

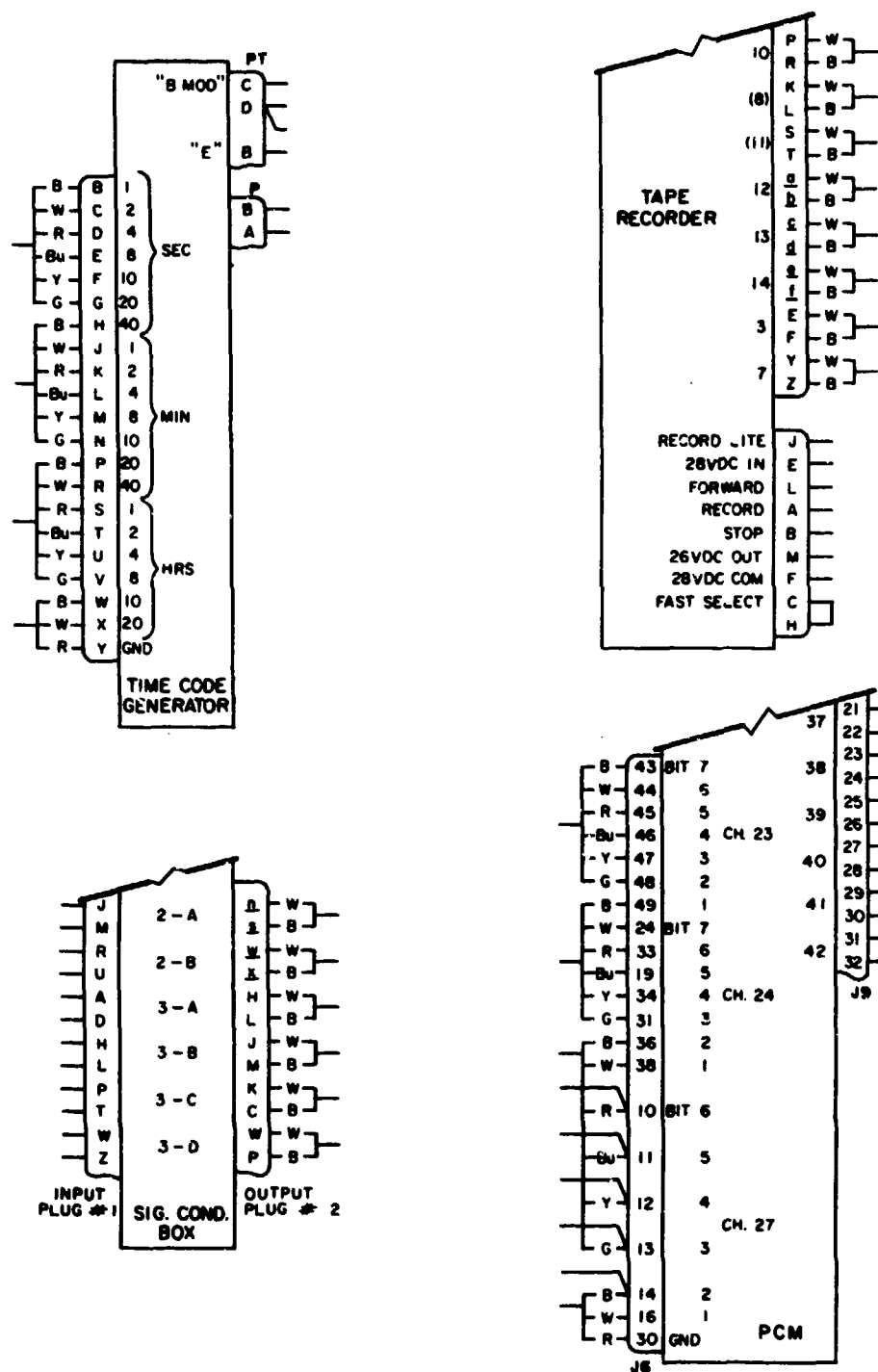


Figure 6.4-3 Examples of Record Keeping as Part of the Wiring Diagram.

6.4.4 The Parameter Line-Up Sheet

One page of a typical hand printed parameter line-up is shown in Figure 6.4-4. The format is designed to assist the engineer and the technician. Transducer and signal conditioning information permit the line-up sheet to represent an up-to-date record of transducer assignment that can be reviewed prior to each flight. The computer, however, has altered all of this record keeping method.

The parameter list shown in Figure 6.4-5 represents one example of a computer print-out in use at the present. The information contained in this form is primarily concerned with only the parameters and the digital system. Instrumentation system record keeping has been deleted. In order to document the transducer and signal conditioning information shown in Figure 6.4-4, additional cards must be punched and another listing made. This procedure has two serious disadvantages. First, it requires additional computer time which is usually not available. Second, in most cases it transfers control of updating the parameter listing from the technician staff to the engineer. Formal documentation now depends upon computer availability.

Channel No. 1, airspeed (coarse) is routed through channel A, card No. 1 of the signal conditioning box.

Internal Card Assignment	Parameter	Transducer Connector				Feed Thru		Signal Output	
		+Sig	-Sig	+Exc	-Exc	+Sig	-Sig	+Sig	-Sig
1-Chan A	Airspeed (coarse)	2-k	2-f	2-c	2-p	2-k	2-p	1-Y	1-b
1-Chan B	Airspeed (fine)	2-m	2-h	2-d	2-r	2-m	2-r	1-e	1-j
1-Chan C	Long. Stick	2-n	2-j	2-e	2-s	2-n	2-e	1-n	1-s
1-Chan D	Lat. Stick	2-w	2-v	2-t	2-x	2-w	2-t	1-v	1-x
2-Chan A	Rud. Pedal	1-n	1-j	1-e	1-s	1-n	1-s	1-J	1-M
2-Chan B	Yaw Trim	1-w	1-v	1-t	1-x	1-w	1-x	1-R	1-U

Figure 6.4-6 Signal Conditioning Box
Input and Output Contact Assignments.

7.0 SPECIAL CONSIDERATIONS

Each instrumentation system installation is unique. In fact, it's probably safe to state that no two are exactly alike. As a result, ALL installations require special consideration of one kind or another.

Four areas of special consideration were selected for discussion. The first, sneak circuit analysis, was chosen for two reasons. First, the technique is relatively new; and second, experience has shown that instrumentation engineers are oriented towards meeting development and installation deadlines, since the ultimate goal is an operational system. There is usually very little time available for circuit analysis that may or may not discover a design deficiency. An understanding of the type of mistakes most often made during system design and installation can be of benefit to both the engineer and the technician staff.

The second subject, pyrotechnic devices, was selected based on the present trend towards the use of scaled down versions of manned aircraft to accomplish expensive and hazardous testing. This type of flight test vehicle, more so than a full scale vehicle, requires pyrotechnic devices for initiating various types of testing modes, vehicle recovery systems, and flight termination systems. The circuits required to accomplish these tasks are usually designed by the instrumentation engineer. Further, these circuits require input commands from an external source, which infers a need for an antenna installation on the flight test vehicle. For this reason, a third subject, aircraft antenna patterns, was chosen to provide the engineer with a basic understanding of how to interpret antenna radiation patterns.

The final subject chosen discusses the effects of lightning and static electricity. This subject involves several areas of interest for the instrumentation engineer. Foremost, perhaps, is the wire shielding techniques used to control lightning induced currents.

7.1 Sneak Analysis

By definition, a sneak is a combination of conditions which cause an unplanned event. The definition is applied to both sneak circuit and sneak software analysis. However, in this discussion, only sneak circuit analysis will be addressed. Refs. (64, 65, 66).

7.1.1 Sneak Circuit Analysis

Sneak circuits are hidden or unrevealed paths existing in electrical designs which usually appear to be satisfactory, but may under a given set of conditions prevent a desired operation or invite an undesired operation. The analysis does not include component failure. Unfortunately, the expression "sneak circuit" is generally interpreted as pertaining only to the electrical circuit and some unknown hidden or latent problem. This concept is not entirely true, because the sneak circuit, or more appropriately sneak condition, can exist in several forms.

7.1.2 Types of Sneak Conditions

- Sneak Path: The sneak circuit path is the classic concept. Current flows along an unexpected route or 'path.'
- Sneak Timing: This form of sneak problem may cause or prevent the flow of current that activates or inhibits a function at an unexpected time.
- Sneak Indicators: A sneak indicator may cause an ambiguous or false display of system operating conditions.
- Sneak Labels: An ambiguous or abbreviated label may cause incorrect stimuli to be initiated through operator error.
- Sneak Procedures: Incomplete or poorly written instructions may permit improper action during system operations.
- Design Concerns: Factors such as improper or inaccurate redundancy; unnecessary circuit components that may have been disregarded or overlooked are areas of design weakness.
- Drawing errors: Drawing errors may appear in the electrical schematics and/or wire lists, or the two may disagree.

The seven categories of sneak circuit listed here reveal latent potential problems that may develop immediately or long after initial system operation. Although sneak circuit analysis can be applied to any electrical system, its cost effectiveness lies with those sub-systems considered critical, whether large or small, whose failure jeopardize unique or costly larger systems.

Assuming that a typical instrumentation system installation lacks sufficient documentation, can the sneak circuit analysis technique still be useful? The answer is "possibly." The answer is derived from reviewing the results of a variety of projects that have benefited from sneak analysis.

Listed in Table 7.1-1 are the results of a sneak circuit analysis performed on twenty-two different types of systems. Some were ground based and others were airborne vehicles such as aircraft and missiles. This table was organized so that the distribution of each type of sneak condition could be quantitatively reevaluated.

The column entitled "Combined" consists of five basic types of sneak circuits:

- a. Sneak Paths.
- b. Sneak Timing.
- c. Sneak Indicators.
- d. Sneak Labels.
- e. Sneak Procedures.

The two remaining columns, "Design" and "Drawing," bring the total to seven.

Table 7.1-1 Sneak Circuit Distribution for 22 Different Systems.

System	Type of sneak		
	Combined, percent	Design, percent	Drawing, percent
1	11.7	60.3	28.0
2	14.9	0.5	84.6
3	39.0	29.0	32.0
4	24.7	53.4	21.9
5	11.3	5.9	82.8
6	11.5	4.9	83.6
7	10.0	41.4	48.6
8	34.2	15.8	50.0
9	14.8	7.9	77.3
10	13.7	2.2	84.1
11	7.5	10.0	82.5
12	12.5	50.0	37.5
13	27.8	16.7	55.5
14	12.1	0.8	87.1
15	74.2	11.9	13.9
16	13.7	23.9	62.4
17	11.0	4.0	85.6
18	60.5	18.5	21.0
19	97.0	1.6	14.0
20	7.5	10.0	82.5
21	3.7	55.6	40.7
22	25.0	16.7	58.3

After comparing the percentage values in each of the three columns it becomes apparent that drawing errors comprise the dominant sneak problem. By actual count drawing errors dominate in 14 of the 22 systems listed. From the remaining 8, drawing errors rank second in five of them. Knowing that the majority of sneak conditions are drawing errors should tend to focus careful attention to these areas during development of the drawings and associated listings.

7.1.4 Examples of Sneak Analysis Reports

Several examples of the sneak circuit reports have been extracted from References (64, 65, 66) and are presented in Figure 7.1-2 through Figure 7.1-8.

Figure 7.1-2 shows a report on a sneak circuit. The condition was found during an analysis of the B-737 research support flight system. The sneak path would have allowed the 28 volt engage interlock bus to have been shorted to a ground through a suppression diode, which in turn would have caused the relay contacts to weld together, locking the system in the engage mode.

TITLE POSSIBLE POWER TO GROUND SHORT IN ENGAGE CIRCUITRY

DATE 3-18-74

ENGINEER *C. Crawford*
C. Crawford

On 3-17-74

REFERENCES

1. AG-40-010, Basic Revision, Autopilot Engage and "A" - "B" Select
2. AF-61-00, Basic Revision, Autopilot Engage Interlock
3. 737 RSFS Nodal Set 102

MODULE/EQUIPMENT

AFD/B237

EXPLANATION

When the FFD "CMS" Engage Switch relay K1 is energized, a switch is enabled which changes the contact positions of K1 and opens a microswitch which inhibits the KB circuitry. At this time the aileron force limiter solenoid is energized and its contacts change state. If the emergency disconnect switch in B237 is opened, the aileron force limiter solenoid loses power and its contacts return to a normally closed state. If S149 is thrown to its normally open position, a power to ground path exists as shown by the sneak path arrows in Figure 1 (attached). This path exists only momentarily unless the spring loaded switch enabled by K1 is physically held in the engaged position. A similar path exists through the suppression diode of KB also.

POTENTIAL IMPACT

Damage to circuitry

RECOMMENDATION

Place a blocking diode below pin 1 of S149.

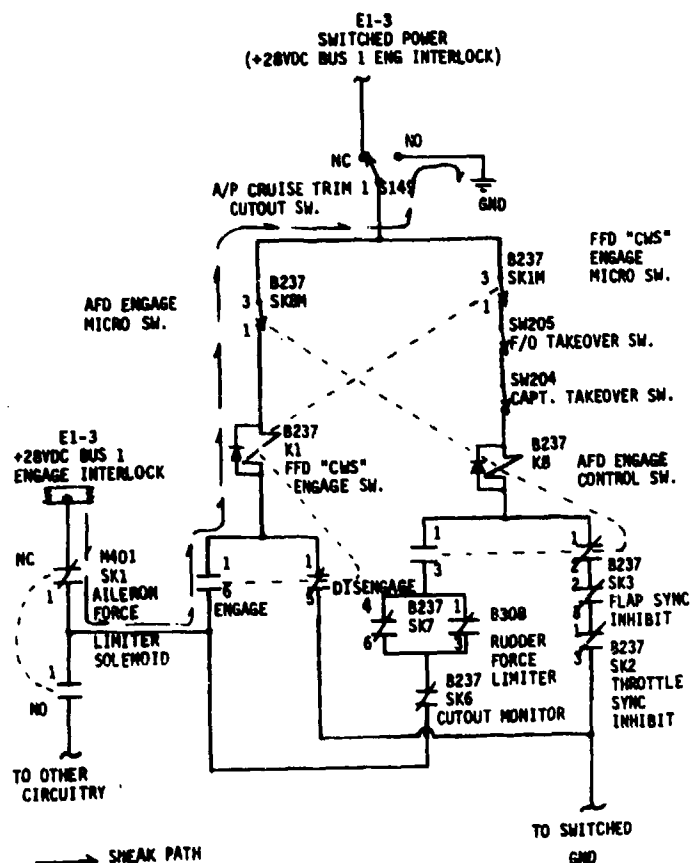


Figure 7.1-2 Sneak Path.

Figure 7.1-3 is an example of sneak timing. The altitude hold switch could be dropped out after being engaged. In addition to being a design concern, this is a problem of timing and is caused by the normal operation of break-before-make contacts in a relay. The problem can be eliminated by changing to a make-before-break relay.

TITLE Altitude Hold Switch May Drop Out After Engagement

DATE 8/19/74

ENGINEER Gordon Buckley

Gordon J. Buckley

REFERENCES

- 1) G.E. Drawing 925C292, Revision C, 1-26-66
- 2) G.E. Drawing 281E402, Revision B, 2-5-74

MODULE/EQUIPMENT

Control Amplifier Part #230E420G4, Ref. Des. 65-AR305

EXPLANATION

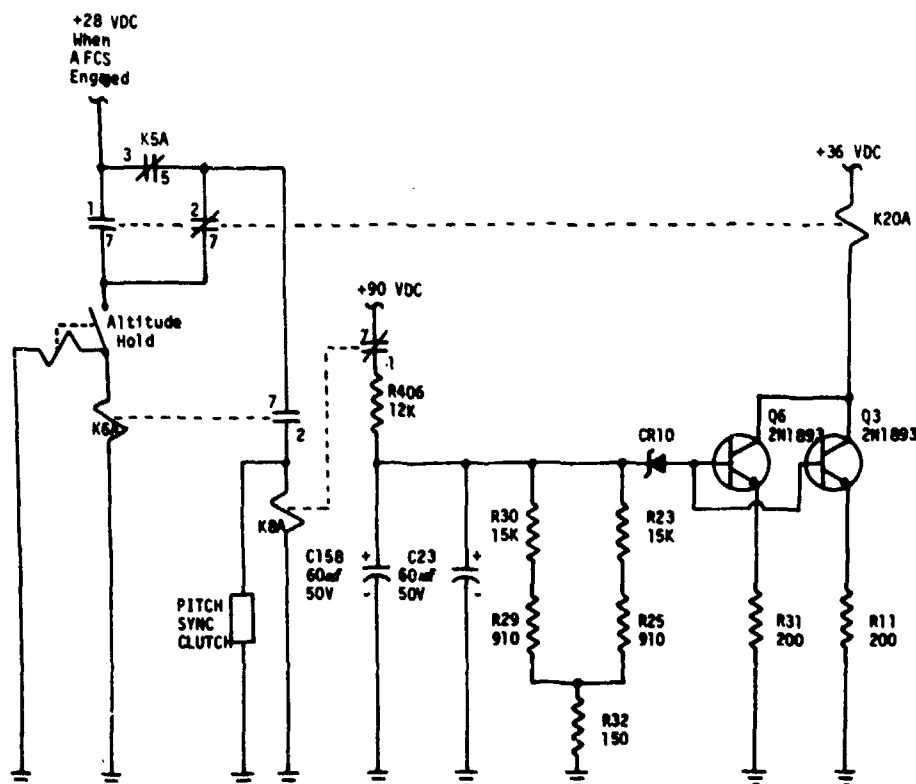
When Altitude Hold Switch is engaged, K5A energizes and closes contact Pins 2 and 7. Then K5A energizes and opens contact Pins 1 and 7, thus removing the 90 VDC from the Adder Attenuator. After C15B and C23 discharge below approximately 21 volts transistor Q3 and Q6 turn off and K20A loses its path to ground and de-energizes. When K20A de-energizes K20A contact Pins 1 and 7 close and K20A contact Pins 2 and 7 open. When these contacts are switching, the Altitude Hold Engage switch loses voltage to its holding coil.

POTENTIAL IMPACT

Altitude Hold may disengage while K20A contacts are switching.

RECOMMENDATION

Replace relay K20A with a relay with make before break contacts.



Contacts shown in normal position during AFCS operation prior to Altitude Hold Engagement

Figure 7.1-3 Sneak Timing.

Figure 7.1-4 shows sneak indicators. A ground indication falsely indicates that four relays are reset when only two of the four are monitored by the indicator. This problem could cause a ground test checkout to verify a circuit that could be failed.

TITLE False Indication Of "IAA Relay Reset" Status

DATE 2-19-78

ENGINEER *J. B. Campbell*
J. B. Campbell

REFERENCES

1. 381093 - Schematic Diagram, PAL/ACS Spacer Sheet 2, Zone 32, 33

MODULE/EQUIPMENT

PAL/A4

EXPLANATION

The indication that IAA relays are reset, as shown in Figure 1, is a false indication. Only relays K5 and K6 are checked by this indication.

POTENTIAL IMPACT

If Relays K3 and K4 fail in the set state and a false "IAA Relays Reset Indication" would be monitored.

RECOMMENDATION

Add relay contacts for K3 and K4 to circuit or change title to "K5 and K6 IAA Rly Reset".

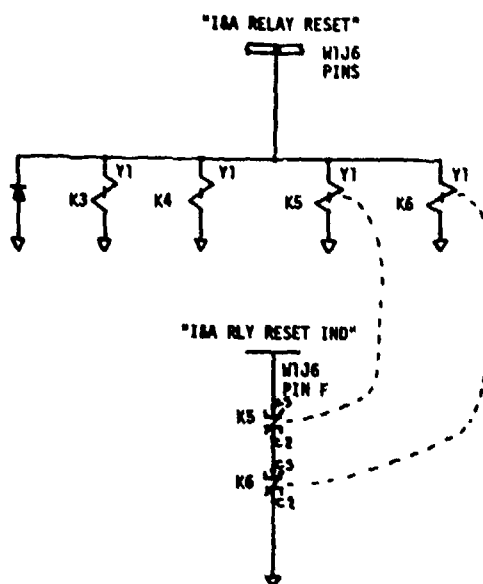


Figure 7.1-4 Sneak Indicators.

Sneak labels are shown in Figure 7.1-5. The sneak label is on a telemetry measurement that indicates that the right landing lights are on. The label, however, indicates "landing lights on." This is an unmanned aircraft, and the measurement could cause the operator to believe that all landing lights are on when only the right landing lights are on.

TITLE

MISLEADING "LANDING LIGHT ON"
TELEMETRY MEASUREMENT

DATE February 22, 1973

ENGINEER *E. Bryen*

REFERENCES

- 1) Electrical and Electronic Wiring Diagram, 225-18005, Rev. G, Page 33-40
- 2) Multiplexer Measurements List provided by Organization 2-2575

MODULE/EQUIPMENT

Air Vehicle/Exterior Lights

EXPLANATION

The "Landing Lights On" measurements shown in Figure 1 are not true under certain conditions. It is possible for the measurements to be on and the LH Landing Lights OFF if CB17 is open. Also, it is possible for the measurements to be OFF and the LH Landing Lights ON if CB18 is open. The measurements shown in Figure 1 actually monitor the RH Landing Light status.

RECOMMENDATION

Rename existing measurements "RH Landing Lights ON"; and add new measurements for "LH Landing Lights On".

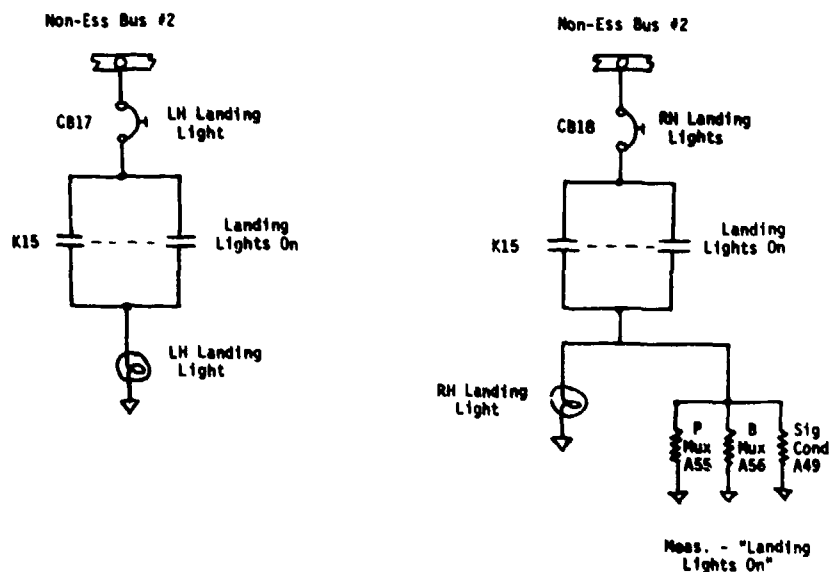


Figure 7.1-5 Sneak Labels.

Figure 7.1-6 illustrates a sneak procedure. The problem involves the lost carrier check, which is supposed to be performed between 7 minutes and 2 minutes before the vehicle is launched. If this check were to be performed, it would activate the timing circuits for the vehicle's drag and main chutes. This would cause the mission to be lost.

TITLE Lost Carrier Check In-effective in
Resetting Recovery System

DATE 12/2/74
ENGINEER Gordon Buckley
-B Gordon B. Buckley

REFERENCES

- 1) T.O. 14750-1, Page 2-86, Flight Controller Manual

MODULE/EQUIPMENT

AGM-38B/Chute Timer

EXPLANATION

If the Lost Carrier Check is performed between seven minutes and two minutes prior to SPA Launch, the following condition exists.

In Step 2 of the Lost Carrier Check, the Chute Timer Reset switch is depressed and the Drag and Main Primer lights go off. In Step 3 the Carrier Test switch is switched to the Carrier Test position and its light comes on. If Step 3 is not initiated within 30 seconds of Step 2, Drag and Main Primer Timing Circuits (Chute Timer) will provide a continuous output which will result in the chutes being released as soon as the SPA is released from the launch aircraft.

RECOMMENDATION

Step 2 and Step 3 should be interchanged.

Figure 7.1-6 Sneak Procedure.

Figure 7.1-7 illustrates a drawing error. This presents the problem of incomplete documentation. Since the usage of the wires listed is unknown to the reviewer, each is assumed to be open ended. (High impedance).

DOCUMENT NO. 2206010	REFERENCE DESIGNATOR See Below	SUBSYSTEM Digital
UNIT NOMENCLATURE Global Signal List		
DISCREPANCY. Listed below are signals and associated connectors which have no apparent "to" termination point. These wires are not labeled as spare or in any other way designated as unused.		
Signal Name	Connector-Pin	Signal Name
+15KWD	AJ09-129	+28VDH
+15TESTD	AJ09-153	+28VDL
+15VD	E000-046	+5KWD
+28KWD	AJ09-140	+5KWD2
+28TESTD	AJ09-155	+5TESTD
+28VDCTA	J017-093	+5TESTZD
+28VDCTB	J117-093	-15KWD
+28VDCTC	J217-093	-15TESTD
		E000-051
		E000-052
		AJ09-118
		AJ09-119
		AJ09-151
		AJ09-152
		AJ09-130
		AJ09-154
(Continued)		
ASSUMED CORRECTION: For the purposes of Sneak Circuit Analysis these wires are assumed to be open-ended. This wire list should be revised to reflect usage of all wiring.		
REPORTED BY B. Alexander	DATE 1-8-76	
SNEAK CIRCUIT GROUP ACTION BY	DATE	
CONTACT NAME	DATE	
CONTRACTOR CONCURRENCE BY	DATE	

Figure 7.1-7 Drawing Error.

Figure 7.1-8 shows a sneak design concern. Part of a flight control amplifier is shown. If any one of the diodes in the three-phase input power fails, the capacitors used in the circuit would fail.

TITLE Capacitor Failure Due to Diode Failure

DATE 7/31/74

ENGINEER P. F. Stokes

P. J. Stokes

REFERENCES

- 1) G.E. Drawing 281E402, Revision B, Dated 2-5-74.
- 2) G.E. Drawing 925C292, Revision C, Dated 1-26-66.
- 3) G.E. Drawing 702C190, Revision C, Dated 3-31-66.
- 4) Illustrated Parts Breakdown, T.O. 5A3-50-4, Change 1, Dated 1 April 1973
- 5) MIL-STD-194C, Dated 29 September 1972.

MODULE/EQUIPMENT

Control Amplifier, P/N 230E42064, Ref. Des. 65-AR305

EXPLANATION

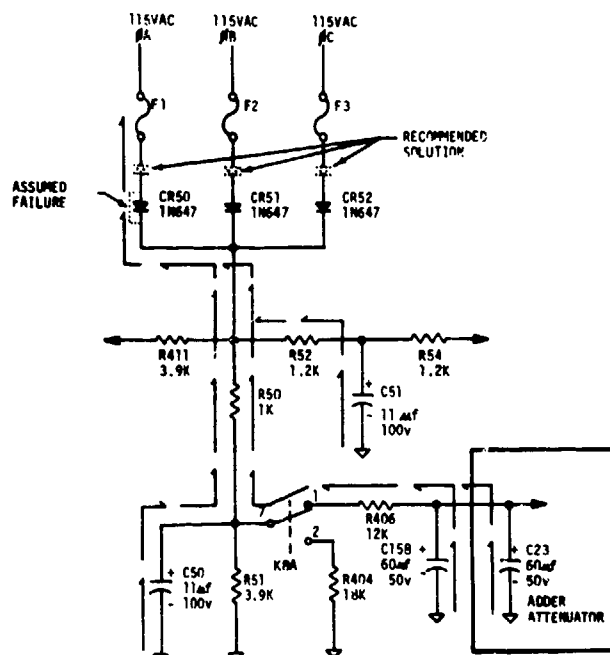
Diodes CR50, CR51 and CR52 rectify the incoming 115VAC, 400 Hz, 3 phase power to provide 135 VDC to the Adder Attenuator and Electronic Switch Monitor. This voltage is filtered by capacitors C50, C51, C158 and C23. C23 is located in the Adder Attenuator Module. The remaining capacitors are chassis mounted components. Should any of the diodes fail in the shorted mode (then fail open) each of the four capacitors will be subjected to reverse current during the negative portion of the cycle for the phase containing the shorted diode. Per reference 4 these capacitors are of the Tantalum Sintered-Slug type. Per MIL-STD-194C, Section A02, paragraph 2.1.2 these capacitors cannot withstand any reverse voltage.

POTENTIAL IMPACT

Capacitors may fail immediately or be damaged to the extent that they will fail later - possibly in flight. Capacitor C51 failure will prevent AFCS from being engaged. Capacitor C158 or C23 failure results in the loss of the pitch fader effect. Capacitor C50 failure results in the loss of both pitch and roll fader effects.

RECOMMENDATION

Add one additional diode in series with CR50, CR51 and CR52 as shown in the attached figure.



DESIGN CONCERN REPORT F-4C-7

REVERSE CURRENT PATH

Figure 7.1-8 Sneak Design Concern.

7.2 Pyrotechnic Devices

Though simple in fundamental concept, the type of pyrotechnic initiator used to perform a given function must be designed for that specific function. The instrumentation engineer must make the proper selection of initiation method, type and weight of explosive charges, housing material, electrical and mechanical connection in order to properly utilize the pyrotechnic-actuated device. Refs. (B11, 67, 68)

On aircraft in general, two basic initiation methods are used. They are:

1. Electrical ignition
2. Percussion ignition.

The electrically-ignited pyrotechnics fall into two categories: (a) the hot bridgewire type, (b) the explosive bridgewire type.

Percussion-ignited pyrotechnics may be initiated by a mechanical means or from a pressure source. In either case, ignition is achieved in the same manner as that of a rifle cartridge.

Both the electrically-ignited and the percussion-ignited initiators can be designed to have either instantaneous or time-delay firing characteristics.

7.2.1 Pyrotechnic Terminology

Under the broad category of pyrotechnics, many names are used to describe any given family member. Until there is a standardization of names, it must be understood that the names initiator, detonator, device, unit, squib, cartridge, and igniter are all commonly used to describe the action performed by a pyrotechnic device.

7.2.2 General Description of Initiators

Most manufacturers make a line of pyrotechnic cartridges with specified charges, sizes, electrical requirements, and actuation times. The standard cartridge contains a primer that can be electrically detonated plus a main charge set off by the primer. A standard cartridge is shown in Figure 7.2-1. A typical booster cartridge is shown in Figure 7.2-2. Notice that the booster cartridge shown is actually two parallel cartridges.

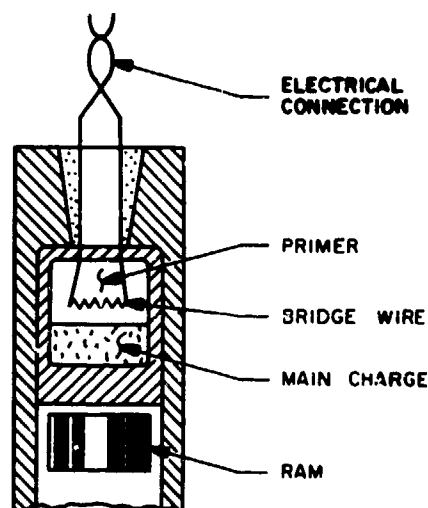
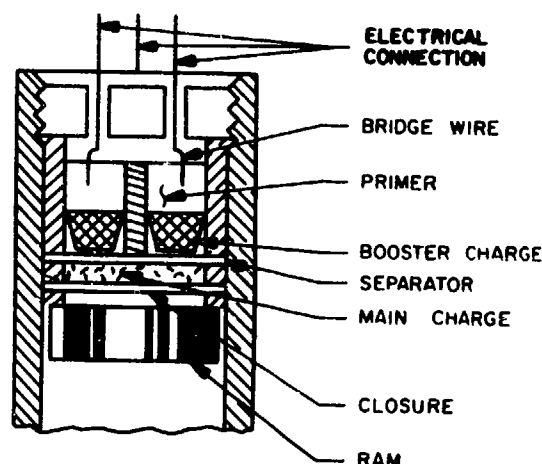


Figure 7.2-1. Standard Pyrotechnic Cartridge.
(Explosive Bridgewire Type)



7.2-2. Typical Booster Cartridge

The first step in sizing the charge is to select an appropriate device for your application. Devices are available in a wide variety of sizes, types, and materials to accommodate different environmental and actuation requirements. For cartridges in general, if the required actuation force is less than 250 pounds, strictly explosive actuation will be the least expensive. Over 250 pounds, a combination of explosive and compressed gas is favored. This type of information and its application is best obtained from the manufacturer of pyrotechnic devices. Most manufacturers will furnish response curves similar to that shown in Figure 7.2-3. Since actuator response and energy requirements are basic needs these types of design curves are very useful.

7.2.2.1 Hot Bridgewire (HBW) Initiators

The most commonly used electrical initiator is the hot bridgewire type, HBW (Figure 7.2-4). The entire initiator assembly is enclosed in a housing similar in appearance to a typical aircraft electrical connector. The pins are carried through a ceramic (or glass) seal, and wires are then attached to the pins. The latest state-of-the-art allows the installation of one to four nichrome bridgewires in a single initiator. However, most initiators use just one or two bridgewires.

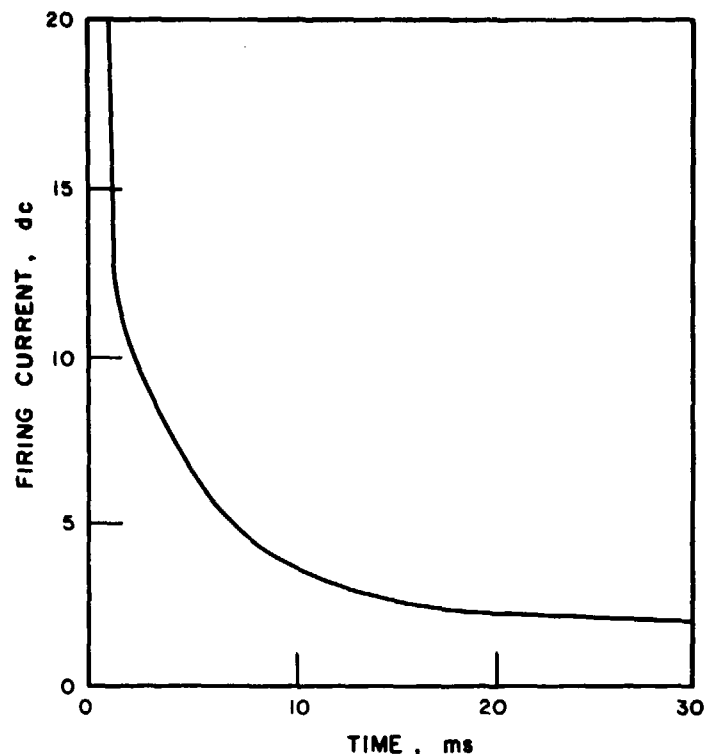


Figure 7.2-3 Typical Actuator Response Time

Recently, requirements have necessitated the development of hot bridgewire units which must have the capability of withstanding one ampere for five minutes and one watt for five minutes without actuation. Prior to this requirement these devices could be fired with as little as one-quarter ampere current. This requirement has stemmed primarily from the need to prevent accidental squib ignition from stray EMI sources.

7.2.2.2 Exploding Bridgewire (EBW) Initiators

The typical exploding bridgewire initiator (Figure 7.2-5) is similar in appearance to the hot bridgewire initiator. One notable difference is a break or gap existing in one of the pins leading to the bridgewire. Another difference is that there is no primary explosive material on the bridgewire in this device. The bridgewire, which is of similar material to that of the hot bridgewire initiator, uses the rapid fusion of the bridgewire itself in response to the high voltage input to ignite the explosive material in this initiator. The EBW initiator is usually somewhat larger than the average hot bridgewire initiator. Due to corona arcing effect in vacuum conditions and the average voltage input to the EBW initiator of 2,000 to 2,500 volts, the electrical pins in the EBW initiator must of necessity be farther apart than those in the average hot bridgewire initiator. Also, the average EBW initiator contains only a single bridgewire.

7.2.2.3 Circuitry Comparison of HBW and the EBW

A comparison of the circuitry required for the EBW and the HBW systems shows that there is more complexity required in the circuitry for the exploding bridgewire. From a low voltage power supply a capacitor portion of the firing unit is charged to high voltage through the arming circuitry. Although conventional shielded-wire cable is sometimes used for a firing lead, coaxial cable is recommended and is often used.

Within the present state-of-the-art, there is no clearly defined way of checking the electrical integrity of the system with the EBW installed. The overall system reliability of the EBW initiator is not expected to be equal with that of the HBW system because of the limited system checkout capability and fewer redundant bridgewires.

In making a choice between an HBW system and an EBW system, the instrumentation engineer should consider the following comparisons.

HOT BRIDGEWIRE

PRO

1. Highly developed state-of-the-art
2. Provides good checkout capability
3. Highly reliable if properly checked out
4. Lightweight
5. Two to four bridgewires offer high redundancy
6. Low in cost
7. Small in size
8. Simple circuitry

CON

1. Mode of failure, after proper checkout, has been premature firing
2. Auto ignition at lower temperatures than most other pyrotechnics
3. Considered to be sensitive to radio-frequency radiation
4. Sensitive to electrostatic charges

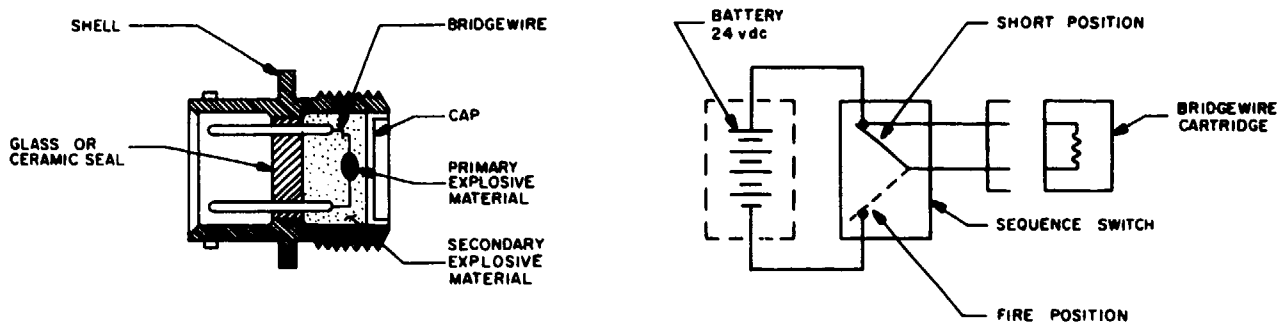


Figure 7.2-4 Hot Bridgewire Initiator and Circuit.

EXPLODING BRIDGEWIRE

PRO

1. Considered to be highly safe from premature firing by transients
2. Initiator will withstand higher temperatures than the hot bridgewire initiator
2. Less sensitive to electrostatic discharges

CON

1. State-of-the-art not highly developed
2. Mode of failure has been failure to function
3. Complex circuitry
4. Costly
5. Lacking in checkout capability
6. Large size

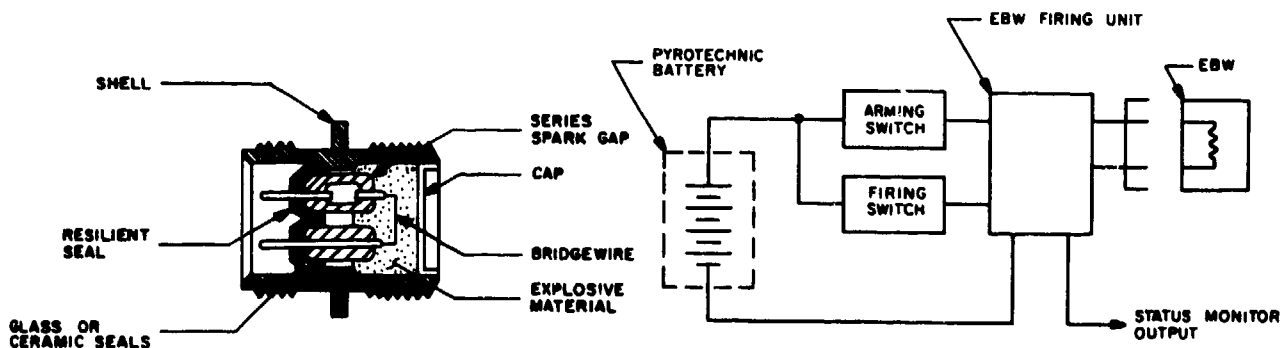


Figure 7.2-5 Exploding Bridgewire Initiator and Circuit.

7.2.2.4 Percussion Initiators

Generally the initiator terminates with a powder charge (see Figure 7.2-6). Ignition is initiated through a percussion cap. Various types of percussion caps are available. The four most commonly used types are the large and small rifle primers and the large and small pistol primers.

There are two basic methods of igniting a percussion initiator. The most often used is a striker or firing pin which is backed by a spring. Retraction of the striker compresses the spring (shown in Figure 7.2-6).

The second method of actuating a percussion initiator is dependent upon pressure. In this type of actuator the striker is usually fixed within the body of the initiator at a fixed distance from the percussion cap (see Figure 7.2-6). It is retained in position by a shear pin.

There is virtually no way to check a percussion initiator prior to firing that will indicate that the device will indeed work; however, percussion initiators have reached a high degree of development over the last 100 years, and there is probably no other item on an aircraft which is made with greater inherent reliability.

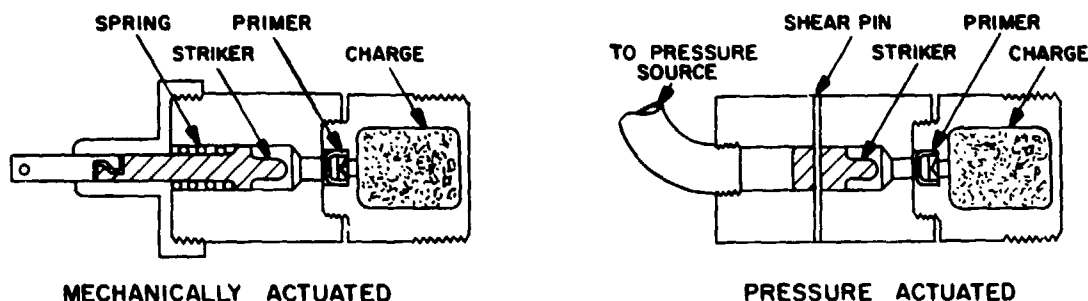


Figure 7.2-6 Typical Percussion Initiator

7.2.3 Connectors and Wiring

All firing leads should be a shielded twisted wire pair or coaxial cable. The pyrotechnic device is usually supplied with unshielded lead wires unless otherwise specified. If shielded lead wires are specified, the shield will probably not be bonded to the device. The manufacturer will usually "float" the shield within the ceramic potting inside the pyrotechnic device. A continuity check between the shield and the device will determine whether or not the shield is floating. One of the two wires should connect one side of the bridgewire to the positive pole on the pyrotechnic battery, and the other wire should connect the other side of the bridgewire to the negative pole on the pyrotechnic battery. Under no circumstances should one side of the bridgewire be grounded to the aircraft structure in a ground-return path. Utilization of a ground return circuit subjects the pyrotechnic system to transients generated by other on-board systems, which may cause premature firing. The pyrotechnic system, on the other hand, can create momentary high current drains which could affect other aircraft systems. Accordingly, the pyrotechnic system should operate from its own battery.

Wiring should not be smaller than AN 20 gage because of mechanical strength considerations. The shield, if grounded to the aircraft airframe, should be grounded at one end only, and when electrical connectors are required, the shield should be carried through the connector on one pin of the connector.

Reliable electrical connectors should be used on all pyrotechnic circuits. These should be of the type that have a positive locking feature. It would be an advantage to have a minimum number of connectors; however, this is not usually possible. For the engineer it would be convenient to firmly lock all connectors after the first hook-up and verification. To achieve comparable reliability, redundant circuits are recommended whenever certain functions must occur. The redundant circuit should have its own separate battery which is completely isolated from the other system. Here again, the use of a separate power source precludes transient firing of initiators.

In order to protect the power supply for a given pyrotechnic circuit and to be sure that this power supply is available for subsequent firings, fuses are required. Fuses, when used, should be of the current-limiting type, because it is just as important that the initiator not get too high a current as it is important that it not get too low a current.

A matching electrical connector should be mated to the initiator at all times prior to connecting the initiator to the aircraft subsystem circuitry. The mating electrical connector should have all bridgewire connecting pins in each device shorted to one another; this short should then be shorted to the shell of the connector. This "shorting plug" provides positive protection from inadvertent firing which could be caused by the discharge of static electricity through the hot bridgewire initiator. Protection against static electrical discharge in the aircraft is provided by shorting circuitry applied through normally closed contacts of the firing relay or switch.

7.2.4 Power Sources

The pyrotechnic power source is generally provided from batteries. The most commonly used battery for aircraft use is the silver-zinc wet cell; however, the engineer can select any battery type that meets his needs. High voltage batteries are not recommended for hot bridgewire initiators because of the impermanent make/break activity that can occur after initial firing.

7.2.5 System Design Philosophy

The design of pyrotechnic cabling is essentially the same as for any other electrical system. There is a wide variety of electrical initiators that can be used to develop a pyrotechnic subsystem for the manned or unmanned aircraft. Because these devices may be similar in appearance and because these devices may be located adjacent to or in close proximity of each other, the engineer must use careful physical layout design. The engineer must develop an installation that precludes incorrect mating of adjacent initiator connectors.

The electrical connectors should not interchange with initiators in close proximity to one another which have different sequencing times. Each initiator should have its own uniquely different connector indexing, pin size, or number of pins.

It is very important that in order to decrease the possibility of radiation hazards, the hot bridgewire units utilize shielded wire where the shield is passed through each connector on one pin in the connector. Again, grounding at one end only is vitally important.

7.2.6 Pyrotechnic System Checkout

The hot bridgewire initiator affords the best checkout prior to flight of any type of pyrotechnic initiator. This observation, although subjective, is based on experience and opinions of a variety of users.

Resistance readings of all circuits should be documented during buildup of the pyrotechnic circuitry and should be checked prior to flight at least once with live pyrotechnic firings. It is important to remember that only a very low energy checkout galvanometer should be used to check the integrity of the pyrotechnic bridgewire, since a high-energy galvanometer may tend to render the primer mix inoperative. A very high energy galvanometer would probably fire the device. Properly trained personnel following well-written procedures are of utmost importance if the reliability which is desired is to be obtained.

7.2.7 Static Charges and Unexpected Firings

In general, manufacturers as well as users have determined by thorough testing that "no fire" and "sure fire" ignition levels are guaranteed to trigger the device within the required time interval.

Theoretically, it should be easy to control the firing circuit within the "no fire" - "sure fire" limits. However, electrostatic discharges and induction from RF sources can sometimes provide enough energy to set off an initiator. Unfortunately, even the static generated by human body movement during system assembly can fire these devices.

The amount of static charge that triggers premature firing can be less than 1/3,300 of the "sure-fire" ignition level. The physical process that permits this premature firing on such a small electrical charge is not well understood; thus, rules for preventing static firing are derived from experience, rather than theoretical sources.

The recognized acceptable test most commonly used by manufacturers and systems engineers is to charge a 500 pf capacitor to a level of .02 joule (200,000 ergs) and to discharge it into the cartridge. Unfired cartridges pass the test!

Another electrical hazard is current induced in the firing circuit by electromagnetic fields. Nearby radar installations, aircraft transmitters, power lines, or broadcast transmitters are typical sources. The best way to estimate induced currents is to perform an on-site measurement of actual electromagnetic

field strength. In most cases, the low frequency end of the spectrum is the most crucial, but the higher frequencies can be important if they are nearby. Proper circuit shielding and adequate grounding of the vehicle and personnel during system installation and test will usually eliminate these problems.

7.2.7.1 Radio Frequency (RF) Effects On Electro-Explosive Devices

Electro-explosive devices (EED) are ignited by an electrical squib or initiator. The squib usually consists of a small bridge wire (fuse) surrounded by an explosive compound. The bridge wire is electrically insulated from its metal case (and ground). The ignition of the explosive material is achieved by passing a current through the bridgewire; this generates a temperature rise, causing the explosive material to detonate. This current flow can be induced by stray electromagnetic fields. The energy required depends upon the squib characteristics, such as the type of bridgewire and the explosive's thermal properties.

As noted elsewhere, the most commonly used electrical initiator or squib is of the bridgewire type. As a result the bulk of the studies relating to EED's and RF are concerned with this type. This type of EED contains one or more bridgewires connected electrically on the input side to metal pins through which the electrical firing current originates. The output side of the circuit is connected mechanically to the explosive material.

Unwanted electrical energy such as RF can also enter on these input pins; the RF energy may also appear between the pins and the case or between the bridgewires in the case of multi-bridgewire squibs. Ref. (69).

7.2.7.2 Pin-To-Pin/Bridgewire Behavior

As a general rule, in the range of 1 to 1000 MHz, the CW-RF sensitivity of a typical squib in terms of average power is equal to or less than the dc sensitivity. That is, a 1 watt "no fire" squib would tend to withstand more CW-RF power than a squib with a "no-fire" of 250 milliwatts. Thus, initiation appears to be mainly a matter of bridgewire heating.

However, above 1000 MHz the pattern is not the same as that below 1000 MHz. For example, arcing frequently occurs and may exist between the bridgewire and the case. This mechanism of firing results in a spread in data that limits a general rule like the one for frequencies below 1000 MHz. Although the rule may still be applied, it must be done so with the knowledge that a risk factor is involved.

Generally, CW-RF and pulsed RF results are similar, except that arcing is much more likely due to "thermal stacking" above 1000 MHz. Pulse widths of 1.5 to 3.0 microseconds and pulse repetition rates from 500 to 2000 have not indicated any large variations in squib sensitivity.

"Thermal stacking" refers to the conditions where the amount of heat in the bridgewire and its immediate surrounding area has not been completely dissipated by the time the next pulse arrives. The effect then is that successive pulses cause a heat buildup which can produce detonation or "dudding." "Dudding" is produced by a decomposition of the explosive material in the immediate vicinity of the bridgewire.

7.2.7.3 Pin-To-Case Behavior

Firing or dudding of EED's in the pin-to-case mode due to CW-RF energy is generally a function of voltage stresses applied between the pins and the case. The initiation will occur whenever the pin-to-case impedance is such that large voltages can be produced with low power levels; this will occur for low values of conductance. These low values usually occur at frequencies in the vicinity of 1.5 MHz.

Pulsed RF and the pin-to-case combination represent a very sensitive condition. In addition, the firing sensitivity appears to have no direct relationship to the dc sensitivity. For example, several 1 amp/1 watt devices showed a high sensitivity to RF pulsed energy. During testing, power levels below 100 milliwatts were frequently sufficient to cause initiation.

Probable causes of RF sensitivity are illustrated in the following example.

a. Example one:

Figure 7.2-7 illustrates two cases of bridgewire support. Figure 7.2-7(a) shows the bridgewire as carried only halfway across the metal support posts, while Figure 7.2-7(b) shows the bridgewire overhanging the posts. (a) represents an ordinary bridgewire configuration. However, (b) illustrates an abnormal condition which encourages arcing. Careful examination of (b) showed evidence of burn marks at the ends of the wire and on the inside of the metal case.

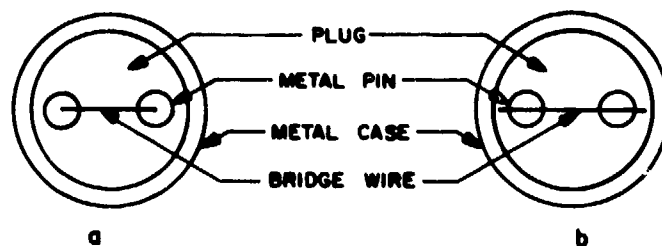


Figure 7.2-7 Overhanging Bridgewire

b. Example two:

Figure 7.2-8 shows metal burrs on the bridgewire posts. Examination of the posts showed that arcing had occurred between the burrs and the case. Microscopic examination of the burrs on the posts indicated that they were the result of a grinding operation.

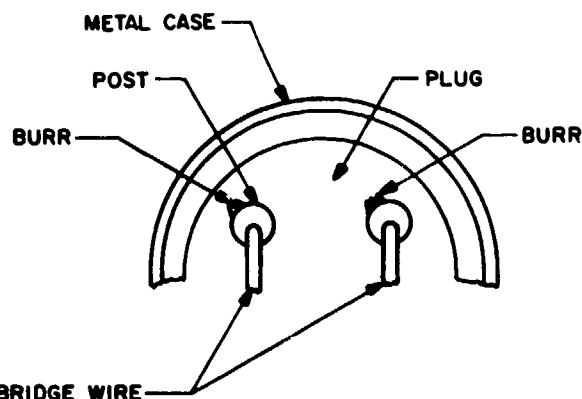


Figure 7.2-8 Metal Burrs on Bridgewire Posts

c. Example three:

The addition of zirconium or aluminum to the explosive mixture is normally done to increase the heat transfer characteristics of the EED. These conductive particles (insulated from each other by the mixture) tend to increase the field intensity within the mixture when pulsed RF energy is present. The overall RF vulnerability problem is one that not only includes the EED but also the circuits that are part of the installation. An insensitive EED carelessly handled in an RF environment or assembled into a poorly-designed circuit may be just as hazardous as a sensitive EED.

7.2.8 Disposal and Inerting

1. All EED's, unless positively identified as expended or inert, shall be treated as hazardous and shall be disposed of in accordance with existing procedures.
2. EED devices rendered non-explosive may be used for mockup, simulation, or similar purposes when marked with the word INERT. In addition to being marked INERT, when size permits, holes should be drilled into the device to deface it. Caution: On more than one occasion the above process of drilling holes has resulted in inadvertent firing of EED's. **DO NOT** drill into any EED if there is any doubt as to its being inert.

7.2.9 Pyrotechnic Operations - Safety Checklist

1. Rough handling, exposure to excessive heat, or exposure to high energy radio, radar, or other RF signals may increase the possibility of inadvertent firing.
2. Pyro devices should be handled or the handling should be supervised by competent persons who thoroughly understand the hazards and risks involved.

3. All personnel concerned with hazardous ordnance operations should be thoroughly briefed concerning the specific hazards involved and impressed with the fact that their own safety, the safety of others, and the prevention of material damage depends upon the intelligence and care exercised by themselves and their fellow workers.
4. Supervision must insure that only properly trained and qualified personnel participate in operations or tasks involving pyro devices.
5. Personnel in the vicinity of ordnance or operations involving ordnance must be kept to a minimum.
6. Special warning signs should be posted in the vicinity of the work area to alert personnel that ordnance is present and that only authorized personnel are allowed in the immediate area.
7. No smoking signs must be posted in each ordnance area. Smoking shall be permitted only in authorized smoking areas.
8. Personnel should not have matches, lighters, or other flame producing devices in their possession within the ordnance areas.
9. All personnel handling ordnance items must wear clean, flame retardant non-static-producing coveralls, face shields, and static electricity ground devices. All other personnel in the ordnance control area should wear clean, flame retardant, non-static-producing coveralls with full-length sleeves and trousers.
10. Flashlights used in ordnance control areas must be of an approved type.
11. Only conductive/non-static-producing plastic bags or materials will be used for packaging or in the vicinity of ordnance items.
12. Special care must be exercised to prevent rubbing together, dropping, impacting, or otherwise damaging ordnance items during handling and/or storage.
13. The number of live ordnance items handled at one time must be kept to a minimum consistent with efficient operation.
14. Work must not be performed upon ordnance items except in facilities approved by Safety.
15. EED's will remain in their shipping containers except during actual installation.
16. Ordnance items not installed must not be left unattended and will be returned to their proper storage at the end of the operation.
17. Heat-producing devices and/or electric drills/motors should not be operating within 3 meters (10 feet) of ordnance items except when approved by Safety.
18. All electrical equipment used to check ordnance must be approved by Safety.
19. All test equipment used to perform electrical tests will have a valid calibration seal.
20. Metal shipping containers must be grounded prior to opening the container.
21. The transportation of pyrotechnic devices must be in accordance with the proper procedures.
22. No ordnance operations should begin if an electrical storm is within eight kilometers (5 miles). All ordnance operations in progress will terminate and all personnel should evacuate to a safe area. The supervisor in charge will make the announcement and take the necessary action when notified lightning is within eight kilometers (5 miles).
23. Pyrotechnic devices must not be left unattended at any time.
24. Grounding devices such as conductive foot covers must be used by all personnel handling electrically initiated ordnance during removal or installation. The grounding devices must ground the personnel handling the ordnance device to facility ground.

7.2.10 Circuit Design Considerations

1. Select standard designs and components of known or proven reliability and safety. Design for interchangeability of similar devices.
2. Avoid situations in which the functional reliability of a device or system depends upon the selective fit of any or all parts.
3. Solid state devices must never be used in series with EED leads to control arming or firing. Only mechanical devices such as relays or switches will be utilized.
4. Use a separate power supply for the EED subsystem to provide isolation from all other electrically-powered systems.
5. Use twisted, shielded wire pairs on all EED circuits, and ground the return side of the circuit only at the power supply.
6. All firing circuit leads must be shielded without discontinuities to provide a minimum attenuation (as specified by existing standards). All source circuits must terminate in a female connector.
7. Carefully color code and identify all pyrotechnic wiring in such a manner as to provide visual isolation and recognition.
8. All firing circuit shielding must provide a minimum RFI attenuation (as specified by existing standards). There must be no gaps or discontinuities in the shielding including the termination at the rear of the connectors. Individual circuit shields contained within an overall shielded cable may be terminated by means of very short lead wires, not to exceed one inch.
9. Generally the EED is enclosed in a metal housing which meets the attenuation requirements called for by existing design standards; in these situations the wiring shield may be terminated at the EED connector. There must be 360° shielding between the shield and the EED housing.

Caution: In general EED's are supplied with unshielded wire-pairs. Even though the engineer may specify "shielded wire pairs" the shield will probably not be grounded to the EED housing.

10. Shields must never be used as intentional current-carrying conductors.
11. Cables may be fabricated such that several EED circuits are contained within a common shielded cable bundle. There should be no splices within the cable bundle(s). Whenever connecting or disconnecting of a circuit is required, a connector will be used in the design.
12. The EED lead wires should not be routed through any connector which also contains any power wiring. It is very important that all firing circuits be physically isolated from any power, control checkout, monitor, continuity, and non-simultaneous firing circuits.
13. Connector pairs should be carefully selected and designed so as to provide non-interchangeability. There should be only one wire per contact. All connectors should be safety-wired.
14. Minimum wire size of AN 20 gage should be considered on the basis of physical strength.
15. All EED's must remain electrically shorted until firing.
16. Logic and EED electrical grounding points must be isolated electrically and physically.
17. All power-source negative lines should be returned to vehicle ground point individually.
18. No flight connectors are to be broken (demated) to perform systems checkout.
19. Manual backup switching must be provided on all crew-safety functions.
20. Redundant relays should always be mounted in such a manner that the vibration axis of one relay is orthogonal (90°) to the sensitive axis of the other relay.

21. Adequate and accessible test points should be provided for checking all elements and circuits.
22. Provide for sneak-circuit analysis of all firing circuits.

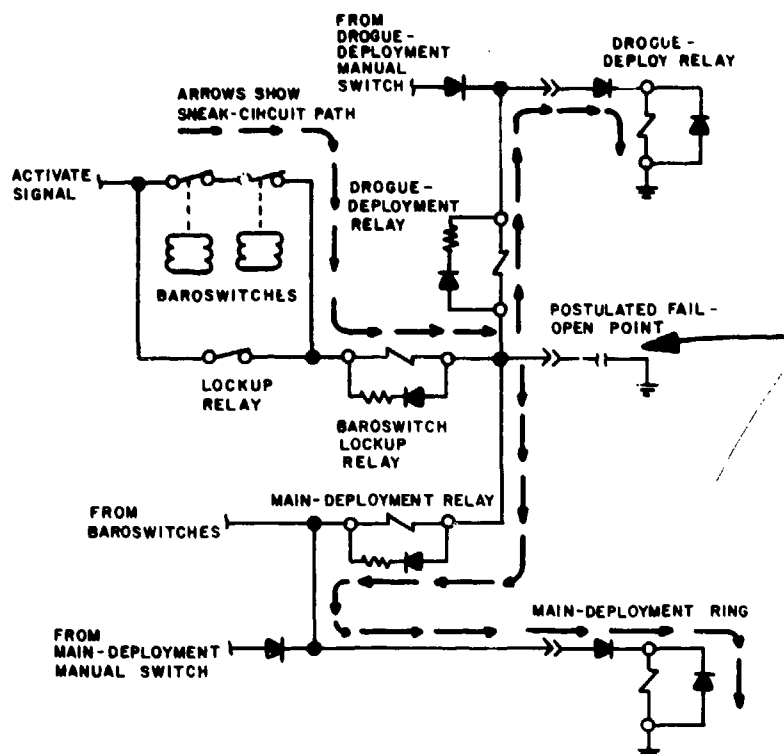


Figure 7.2-9 Parachute Deployment "Sneak" Circuit Simplified Drawing

In the above figure if the single ground connection (shown as "postulated fail-open point") should open, then a sneak circuit would exist that could result in deploying the drogue and pilot parachutes. This sneak circuit was created when wiring modifications were made external to an electrical chassis. The modifications nullified the original design of the chassis and allowed circuit paths to exist that the original designer had never planned. This example should be sufficient to point out the need for proper documentation and documentation review.

7.2.11 Documentation

Primary effort should be expended on procedural documentation of pyrotechnic systems. The procedures should provide for inspection and testing upon delivery/acceptance of the initiator. Procedures should be written which carefully detail aircraft pyrotechnic firings. Accurate detailed wiring diagrams are a must so that system discrepancies encountered during testing can be properly identified and immediately corrected. Any detail that is overlooked in the installation and checkout procedures could contribute to premature termination of a mission or mission failure. Be aware of the total environment in which the system must operate. For example, RF transmitting systems located along the taxi-way, etc.

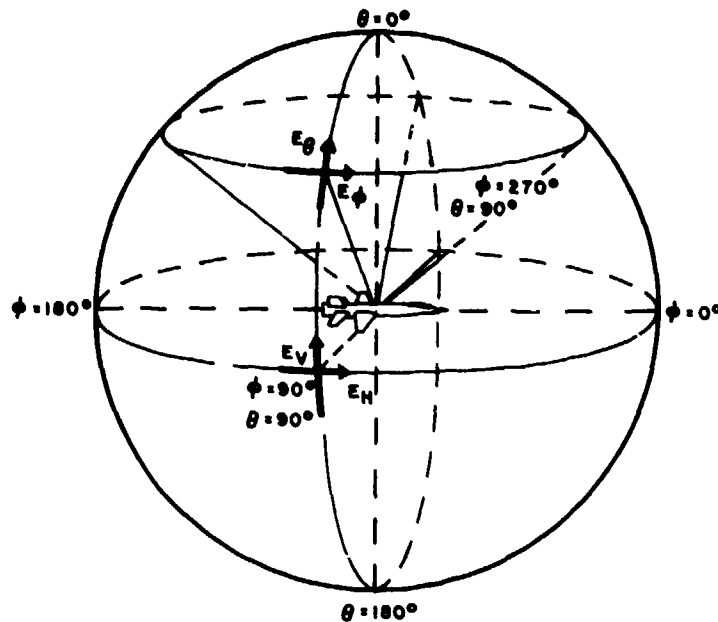
7.3 Aircraft Antenna Patterns

The instrumentation engineer usually has responsibility for ensuring that his airborne data acquisition system delivers data to either an on-board recording system or to a receiving ground station by use of telemetry. Oftentimes a combination of both methods is necessary. The use of an on-board recording system usually does not present any problems; however, an on-board telemetering system may be a cause for concern. Although the on-board telemetry system may be well designed, the telemetry transmitter must interface with an antenna mounted somewhere on the aircraft. The location and radiation pattern of this antenna is very important because the radiation pattern must be visible to the ground tracking antenna during all aircraft attitudes.

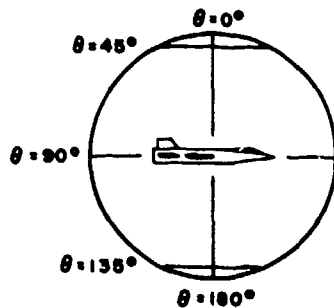
The location of an antenna on an aircraft can only be considered adequate after evaluation of the antenna's radiation patterns. For most circumstances radiation patterns cannot be performed on the test aircraft. As a result, scale modeling techniques are used to optimize the antenna location and radiation patterns. The net result is that the instrumentation engineer is often presented with a set of radiation patterns that need his approval. In most cases the instrumentation engineer is unfamiliar with the terminology and does not fully understand how to interpret the radiation patterns.

7.3.1 The Coordinate System

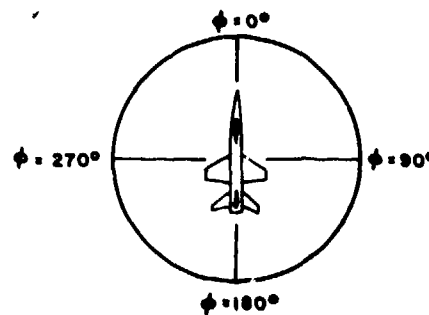
The spherical coordinate system is generally used for analyzing antenna model radiation patterns. Two angular coordinates which may be used are shown in Figure 7.3-1; these are the phi (ϕ) coordinate and the theta (θ) coordinate. The direction of the polar axis Z ($\theta = 0^\circ, 180^\circ$) of this coordinate system is chosen to be whatever is appropriate for the antenna being evaluated and the corresponding conical pattern is shown in Figure 7.3-2. A more complete understanding of how this coordinate system is used can be done by using actual antenna patterns. Refs. (B12, 70).



(a) Coordinates θ and ϕ



(b) Coordinate θ



(c) Coordinate ϕ

Figure 7.3-1 The Spherical Coordinate System

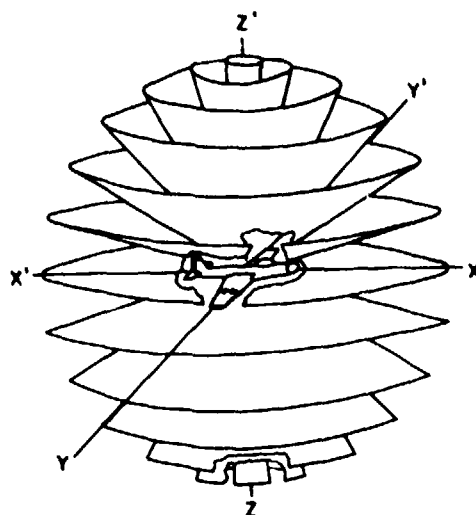


Figure 7.3-2 Conical Pattern Around the Z-Z' Axis.

7.3.2 Explanation of Antenna Patterns

The examples shown utilize the polar chart method of presentation. This method is generally used when the antenna patterns presented are very broad in their coverage as is the circumstance for all aircraft telemetry antennas. Antenna installations that present a narrow pattern are generally plotted on rectangular chart paper.

Figure 7.3-3 presents a "side-view" or "pitch-plane" of an antenna radiation pattern. Notice that the direction of the polar axis Z ($\theta = 0^\circ, 180^\circ$) has been chosen to be horizontal rather than vertical on the polar chart. This location corresponds with the letter (A) as described below.

A universal or standardized polar chart form does not exist and as a result the instrumentation engineer is confronted with a variety of forms. However, all polar chart forms must, as a minimum, present the information shown in block (F). The information in blocks (A), (B) and (C) must be contained in an attached data sheet.

Parts of Figure 7.3-3 have been identified with either a number or a letter. The numbers are used to assist in pattern correlation (see Figure 7.3.3) and the letters are used to assist in describing the polar chart as explained below.

- (A) As shown in the block panel, the 'X' has indicated that the radiation pattern shown is in the "pitch plane" or, more exactly, the geometric plane shown in Figure 7.3-1(b).
- (B) The information to be supplied here identifies the type of aircraft, the antenna location, and model scaling details. The scale model used for the polar pattern shown is a 1/20 scale X-15A-2. Notice that block (A) indicates a B-52. Any type aircraft can be used here. Its sole purpose is to indicate the "plane" in which the pattern is made. Frequency is related to wavelength and the ratios are directly proportional. The full scale aircraft telemetry frequency is 281 MHz. In order to maintain scale model/wavelength relationship the frequency must be increased twentyfold. Thus $281 \text{ MHz} \times 20 = 5620 \text{ MHz}$ or 5.62 GHz, the scale model test frequency used. The large areas of metal that form airplane surfaces are essentially perfect reflectors for RF waves at all frequencies, so that if a good conductor such as copper is used in the model, scaling errors will be negligible. However, keep in mind that modern day aircraft and remotely piloted vehicles use surface materials such as Fiberglass and other composites. These variations in conductive skin surfaces must be taken into consideration.
- (C) The amplitude patterns of an antenna are usually plotted in terms of voltage (electrical field intensity), although power is sometimes used. An alternate form employs decibels; this is particularly useful for presenting patterns with minor lobes and nulls. When decibels are used the major lobes are usually narrow, and, as stated earlier, plotted on rectangular charts.

Gain as a voltage ratio:

$$\text{dB} = 20 \log G \text{ (voltage)} \quad \text{Eq. (7.3-2)}$$

The dB gain is the same whether it is based on power or voltage ratios. A half-wave dipole has a power gain of 1.64 and a voltage gain of 1.28 relative to an isotropic antenna. Expressed in decibels the gain is 2.15. In the example shown in Figure 7.3-3 the gain of the isotrope is unity or 0 dB. In its proper form, the gain of an antenna must be stated in reference to the tested procedure. For example, a typical antenna may have a gain of 5.0 dB as referenced to an isotropic antenna or only 3.85 dB as referenced to a half-wave dipole.

- ④ & ⑤ Where transmitting antennas are concerned, the importance of field intensity must not be overlooked. The scale, mv/meter at 1 mile for 1 watt is standard and can be correlated with decibels as follows:

Isotropic radiator (a radiator that radiates energy uniformly in all directions):

The power density P at a point due to the power W_t radiated by an isotropic radiator is

$$P = \frac{W_t}{4\pi R^2} \text{ watts/meter}^2 \quad \text{Eq. (7.3-3)}$$

where R = distance in meters

W_t = power transmitted in watts

The electrical-field intensity E in volts/meter and power density P in watts/meter² at any point are related by

$$P = \frac{E^2}{120\pi} \quad \text{Eq. (7.3-4)}$$

where 120π is known as the impedance of free space.

From Eq. (7.3-3) and Eq. (7.3-4)

$$E = \frac{(30 W_t)^{\frac{1}{2}}}{R} \text{ volts/meter} \quad \text{Eq. (7.3-5)}$$

if $R = 5,280$ ft/statute mile thus $R = 1609$ meters then

$$E = 3.4 (\text{mv/meter})^{\frac{1}{2}} \quad \text{Eq. (7.3-6)}$$

Relating the isotropic reference antenna field intensity to dB:

$$E = 3.4 (W_t)^{\frac{1}{2}}$$

$$E^2 = 11.56 W_t$$

$$\text{then } W_t = 0.0865 E^2 \quad \text{Eq. (7.3-7)}$$

taking logarithms of both sides

$$\begin{aligned} 10 \log W_t &= 10 \log 8.65 \times 10^{-2} + 20 \log E \\ &= 10 \log 8.65 - 20 \text{ dB} + 20 \log E \\ &= 9.37 \text{ dB} - 20 \text{ dB} + 20 \log E \end{aligned}$$

$$\log E = \frac{10 \log W_t - 9.37 \text{ dB} + 20 \text{ dB}}{20}$$

if $W_t = 1$ then $10 \log W_t = \text{zero}$.

$$\begin{aligned} E &= \log^{-1} \frac{10.63}{20} = \log^{-1} 0.5315 \frac{\text{dB}}{\text{iso}} \\ &= 3.4 \text{ mv/meter at 1 mile for 1 watt} \end{aligned} \quad \text{Eq. (7.3-8)}$$

The isotropic circle (shown in dotted lines) will therefore intersect both 3.4 mv/meter/watt at 1 mile and 0 dB. A 4 dB circle intersects 5.4 mv/meter/w at 1 mile, and so forth. (See Figure 7.3-3).

- Ⓕ This blocked area contains all the information required to identify the radiation pattern. The variable angle marked θ indicates that the radiation pattern is in the vertical plane. This is verified by the constant angle ϕ marked as zero. Refer to Figure 7.3-1(b) and (c). The aircraft model was rotated through a full 360° or θ values of zero to 180° then continuing around from 180° back to zero. Notice that the value of $\theta = 0^\circ$ is the top of the aircraft in both Figure 7.3-1 and Figure 7.3-3. This standardized notation will always permit proper user orientation. During the model rotation the horizontal plane ϕ remained fixed or constant.

The properties of a wave propagating in free space may be obtained through the use of Maxwell's equations, which stated in vector form in MKS units is expressed as follows (see Figure 7.3-4):

H, the magnetic field intensity, amperes/ meter; E the electric field intensity in volts/meter.

E and H are mutually perpendicular and can be rotated as required. For example, E lies in the Y axis plane. H lies in the Z axis plane and is propagated along the X axis.

It logically follows then that if E was chosen to represent antenna polarity then a vertically polarized antenna would have E in the Y plane. If we rotate E and H 90° then E lies in the Z plane and H lies in the Y plane. An antenna that radiates E in the Z plane is then referred to as horizontally polarized. Refer-

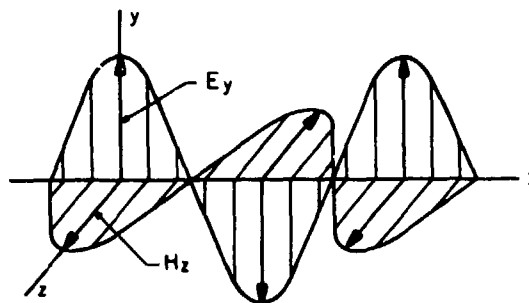


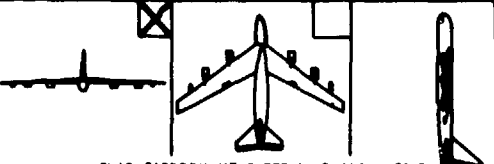
Figure 7.3-4 Sinusoidal Propagation

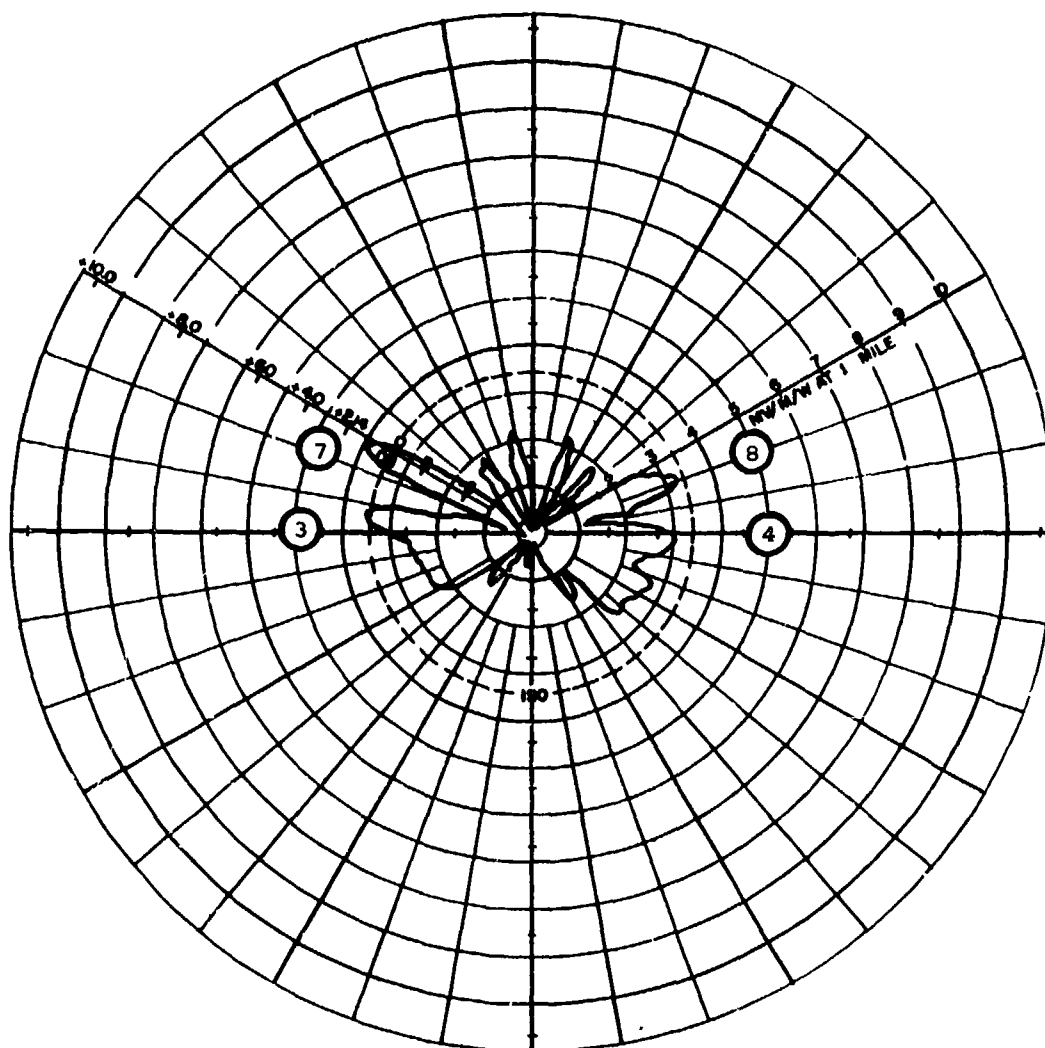
ring to block Ⓕ and Figure 7.3-1(b) and (c), E_ϕ is notation for horizontal polarity and E_θ is notation for vertical polarity. Since E is defined as volts/meter then it follows that the isotropic level Ⓒ is shown as millivolts/meter.

- Ⓖ This block is generally used to identify the aircraft and its configuration. This information is important because antenna tests are usually representative of a basic aircraft in flight configuration. Changes to the basic aircraft must be noted. Changes such as landing gears extended, external stores mounted on the fuselage or wings can alter the basic antenna pattern. Military aircraft may have dozens of external configurations and additional antenna studies are required to determine the effect on the basic radiated pattern. An engineer who has spent months optimizing an antenna installation on a basic aircraft is justified in being disappointed when external stores are added to the aircraft later on. The operator's name and date as well as approval is optional and required only for internal control.

7.3.3 Pattern Correlation

The antenna patterns shown in Figure 7.3-3 and Figure 7.3-6 will be correlated first. Figure 7.3-3 is the "pitch-plane" radiation pattern discussed earlier and is fully contained within the aircraft's longitudinal θ coordinate. Figure 7.3-6 is a conical pattern as identified by ϕ as the variable angle and $\theta = 70^\circ$ as the constant angle. Since the conical radiation pattern lies within the ϕ coordinate, only two points can intersect. These are shown as ① and ①A, ② and ②A. The radiation pattern values for points ① and ①A should be the same value and they are. Comparing points ② and ②A shows that they are very close to the same value. All the conical patterns can be correlated with this pitch radiation pattern in this manner. Pairs of points should compare to within a tolerance of ± 2 dB.

 <p>THIS PATTERN MEASURED IN PLANE CHECKED</p>	FILE NO _____	SHEET <u>2</u> of <u>42</u>
	PLANE TYPE <u>X-15A-2</u>	MODEL SCALE _____
	ANTENNA TYPE _____	
	ANTENNA LOCATION _____	
	FREQUENCY FULL SCALE _____	MODEL _____
MODEL SURFACE _____		



REMARKS _____	VARIABLE ANGLE θ (), θ (X)
_____	CONSTANT ANGLE $\theta = 90$ $\theta =$ _____
OPERATOR _____ DATE _____	POLARIZATION E_{θ} (), E_{θ} (X), _____
APPROVED _____ DATE _____	θ = HORIZONTAL ANGLE θ = VERTICAL ANGLE
	CURVE PLOTTED IN: VOLTAGE (X), POWER (), DECIBELS ()

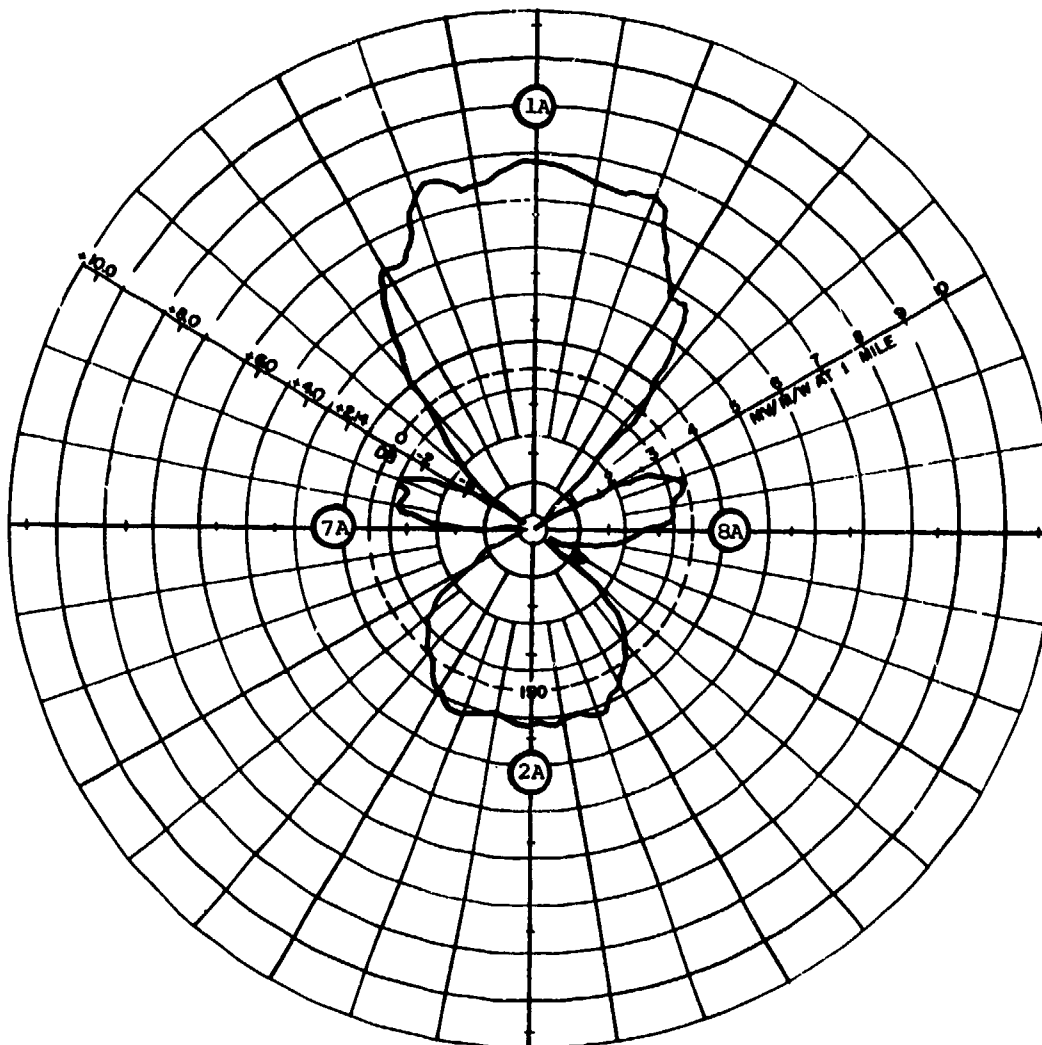
Figure 7.3-5 Polar Recording Chart

The next two radiation patterns to be correlated are Figure 7.3-5 and Figure 7.3-7. Figure 7.3-5 is a tail-on view of the aircraft radiation pattern and is fully contained within the θ coordinate perpendicular to the pitch plane θ coordinate. Figure 7.3-7 is a conical pattern existing at $\theta = 90^\circ$. The radiation pattern values for points ③ and ③A should be the same and they are well within the ± 1 dB tolerance. Points ④ and ④A should be the same value and they are.

Further pattern correlation can be achieved with Figure 7.3-3 and Figure 7.3-7. These two patterns intersect at the nose ($\theta = 90^\circ$, $\phi = 0^\circ$) and the tail ($\theta = 50^\circ$, $\phi = 180^\circ$). The points ⑤ and ⑤A, ⑥ and ⑥A compare very well.

One final pattern correlation can be done with Figure 7.3-5 and Figure 7.3-6. Figure 7.3-6 is the 70° conical pattern and intersects Figure 7.3-5 at $\theta = 70^\circ$. The points ⑦ and ⑦A and ⑧ and ⑧A compare within the ± 2 dB tolerance established earlier.

	FILE NO. _____	SHEET <u>10</u> OF <u>42</u>
	PLANE TYPE <u>X-15A-2</u>	MODEL SCALE _____
	ANTENNA TYPE _____	
	ANTENNA LOCATION _____	
	FREQUENCY FULL SCALE _____	MODEL _____
MODEL SURFACE _____		



REMARKS _____	VARIABLE ANGLE Θ (X), Θ ()
_____	CONSTANT ANGLE Θ = _____ Θ = <u>70</u>
_____	POLARIZATION E_{Θ} (), E_{Θ} (X), _____
OPERATOR _____ DATE _____	Θ = HORIZONTAL ANGLE Θ = VERTICAL ANGLE
APPROVED _____ DATE _____	CURVE PLOTTED IN: VOLTAGE (X), POWER (), DECIBELS ()

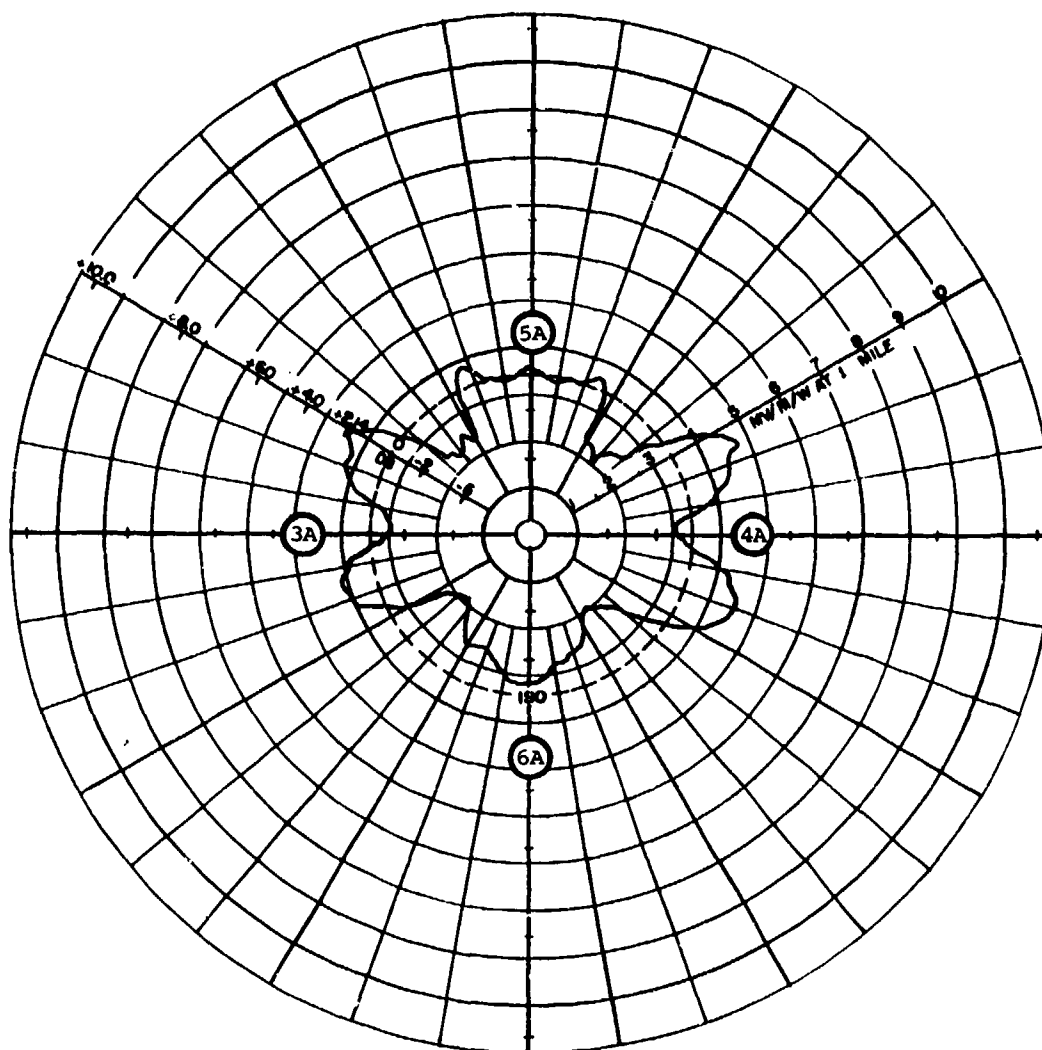
Figure 7.3-6 Polar Recording Chart

Pattern correlation serves two purposes: First, the correlation provides a three dimensional view of the radiation pattern. With a little experience these patterns can be mentally visualized and used to evaluate antenna radiation coverage. Second, the comparison of point pairs (e.g., ① and ①A) provides a check on the precision of how the patterns were made. If these point-pairs did not match within ± 2 dB it must be assumed that the test procedure or the equipment was faulty. Careful, continual system calibrations are necessary.

7.3.4 Quantitative Use of Pattern Data

The following example developed from data taken from Figure 7.3-3 illustrates the usefulness of presenting calibrated antenna patterns on polar chart paper.

<p>THIS PATTERN MEASURED IN PLANE CHECKED</p>	FILE NO _____	SHEET <u>12</u> OF <u>42</u>
	PLANE TYPE <u>X-15A-2</u>	MODEL SCALE _____
	ANTENNA TYPE _____	
	ANTENNA LOCATION _____	
	FREQUENCY FULL SCALE _____	MODEL _____
MODEL SURFACE _____		



REMARKS _____	VARIABLE ANGLE θ (X), θ ()
_____	CONSTANT ANGLE θ = _____ θ = <u>90</u>
OPERATOR _____ DATE _____	POLARIZATION E_θ (), E_θ (X), _____
APPROVED _____ DATE _____	θ = HORIZONTAL ANGLE θ = VERTICAL ANGLE
	CURVE PLOTTED IN: VOLTAGE (X), POWER (), DECIBELS ()

Figure 7.3-7 Polar Recording Chart

The field strength incident to the receiving site is found from:

$$E = \frac{(\text{Polar chart value})}{R} \sqrt{W_t} \times 10^{-3} \quad \text{Eq. (7.3-9)}$$

where

E = Field intensity at receiving site
(mv/meter/watt at 1 mile)

W_t = Radiated power in watts

R = Range in statute miles

The actual value of W_t should include mismatch and transmission line losses

From basic antenna theory, combine:

$$A = \frac{W_r}{P_i} \quad \text{Eq. (7.3-10)}$$

$$P = \frac{E^2}{120\pi} \quad \text{Eq. (7.3-11)}$$

$$A = \frac{\lambda^2 G}{4\pi} \quad \text{Eq. (7.3-12)}$$

To obtain:

$$\frac{\lambda^2 G}{4\pi} = \frac{W_r 120\pi}{E^2} \quad \text{Eq. (7.3-13)}$$

where

P = Power density in the incident wave

λ = Wavelength in meters

G = Receiving antenna gain

W_r = Power delivered to matched load by receiving antenna

Assuming that both antenna and the load impedances are 50 ohms:

$$W_r = \frac{V^2}{50} \quad \text{Eq. (7.3-14)}$$

where V = voltage at the receiver antenna terminals. From Eq. 7.3-13 and Eq. 7.3-14 we obtain:

$$V = \left(\frac{\lambda E}{4\pi} \right) \sqrt{\frac{5G}{3}} \quad \text{Eq. (7.3-15)}$$

As an example:

$W_t = 30$ watts

$R = 100$ statute miles

$G = 18$ dB (Power ratio = 63), receiver antenna gain

$F = 281$ MHz, $\lambda = 1.07$ meters

The value of field intensity from Figure 7.3-3 (at point ① the mv/meter value at $\theta = 70^\circ$ off the nose) is 7.6 mv/meter.

$$E = \frac{(7.6) \sqrt{30}}{100} \times 10^{-3} \quad \text{Eq. (7.3-16)}$$

$$= 0.416 \times 10^{-3} \text{ v/meter}$$

$$V = \frac{(1.07)(0.416 \times 10^{-3})}{4\pi} \sqrt{\frac{5(63)}{3}} \quad \text{From Eq. (7.3-15)}$$

$$= 363 \mu \text{ volts} = -55.8 \text{ dBm}$$

The advantages of the quantitative pattern technique can be further illustrated by evaluating the -55.8 dBm signal level derived from Eq. (7.3-15). For example: A -55.8 dBm when compared to a threshold receiver sensitivity of -90 dBm results in a signal strength margin of 34.2 dB. This would indicate that nulls of 10 dB would still leave a usable margin of 24.2 dB signal strength that can be applied to path loss considerations.

Another factor often overlooked is the transmitter power output. It is interesting to note that doubling the transmitter power output is only an advantage of 3 dB. Obviously, this will not compensate for a 10 dB null. However, receiver antenna gain, receiver sensitivity and receiver pre-amps will provide a much better opportunity for obtaining dB gain advantages.

7.3.5 Reciprocity of Radiation Patterns

Instrumentation engineers who review antenna patterns often notice that the polar charts are not labeled as transmit or receive radiation patterns. This is not necessary because of the reciprocity theorem that states "The radiation patterns of a given antenna are the same whether the antenna is used for radiation or reception." Ref. (B13).

The antenna reciprocity theorem is an extension of the reciprocal relations defined in circuit theory as proved by Kirchhoff. In using the reciprocity theorem for antennas and propagation studies it is assumed that the network elements and the propagation media undergo no change with time.

7.4 Lightning and Static Electricity

The early wooden-structured aircraft with metal control cables and strut wires were not capable of conducting lightning strike current; as a result parts of the aircraft sometimes caught fire or exploded. Even if the aircraft was not severely damaged, the pilots were frequently shocked or burned. In some cases the fuel tanks caught fire and exploded. These effects, aided by severe air turbulence and wet weather, quickly taught pilots to stay clear of any areas that even hinted of stormy weather. Ref. (B14).

With the development of metal-skinned aircraft and later on all metal aircraft, the hazardous results of lightning strikes were greatly minimized. However, thunderstorm areas are even today treated with a great deal of respect. In terms of lightning strike damage, the most common referenced are aircraft structural damage. In recent years, however, the trend of thinking is also concerned with secondary or indirect effects. Even though the aircraft's metallic structure provides a high degree of shielding, some of the fields penetrate through windows or other non-conducting materials and induce transient voltage surges in the aircraft's electrical wiring causing systems failures.

Another factor to be considered near thunderstorm activity (and the most common) is precipitation static. If an aircraft is flying through dry precipitation in the form of sleet, hail, or snow, the impact of these particles on the aircraft will cause a phenomenon known as triboelectric charging, commonly called precipitation static or P-static. This process generates interference or static in the aircraft communications and low-frequency automatic direction finding (ADF) system. The results of P-static discharges from the vicinity of sharp extremities on the aircraft produce a visible glow or corona called St. Elmo's fire.

7.4.1 Lightning

The primary or direct effects of lightning generally affect the entire metal aircraft structure, the outer aircraft skin as well as the internal metal framework. Because the lightning currents must flow between an entry and exit points the currents tend to spread out using the entire airframe as a conductor. As a result, physical damage will often occur at a point where poor electrical bonding exists and/or at the entrance or exit points. If sufficient currents, for example, converge at an exit point, the concentration of magnetic forces and resistive heating can cause damage.

Early aircraft designs using wood and fabric construction would have no doubt suffered high statistical damage rates if it had not been for the sincere respect for adverse weather conditions. But the development of the aluminum skinned and structured aircraft permitted flying in and near adverse weather. Because aluminum is a good conductor catastrophic damage from lightning strikes was rare. However, today the trend is again toward the use of non-metallic materials in aircraft construction. Materials such as fiber-reinforced plastic and resinous honeycomb offer advantages in cost and weight. Their use is understandable but these materials have begun to appear at the aircraft extremities where the structural loads are minimal and the lightning strikes are most apt to occur! Typical areas include the nose, wingtips, access doors, horizontal stabilizer tips and rudder tips.

During the last two decades or so it has become increasingly apparent that the direct effects of lightning strikes to aircraft may indirectly cause electronic equipment failure. The indirect effects are caused by the electromagnetic fields associated with the lightning current flowing through the aircraft.

7.4.1.1 Indirect Effects

As lightning current flows through an aircraft it produces strong magnetic fields which surround the conducting aircraft and change rapidly in accordance with the fast changing lightning-stroke current. Some of this magnetic flux will find its way into the aircraft. As a result, these internal fields pass through aircraft electrical circuits and the voltage induced is proportional to the rate of change of the magnetic field. These magnetically-induced voltages may

appear between both wires of a two-wire circuit or between either wire and the airframe. Until the development of solid-state circuitry and its application to aircraft electronics the indirect effects from lightning did not warrant much attention. However, lightning strike reports (civil and military) are showing incidents of avionics damage without evidence of any direct attachment of the lightning flash to the electrical systems.

Table 7.4-1 Evidence of Indirect Effects
in Commercial Aircraft (214 Strikes)
Refs. (B14)(71).

SYSTEM AFFECTED	INTERFERENCE	OUTAGE
HF communications	--	5
VHF communications	27	3
VOR receiver	5	2
Compass (all types)	22	9
Marker beacon	--	2
Weather radar	3	2
Instrument Landing System	6	-
Automatic Direction Finder	6	7
Radar altimeter	6	-
Fuel flow gage	2	-
Fuel quantity gage	--	1
Engine rpm gage	--	4
Engine exhaust gas temperature	--	2
Static air temperature gage	1	-
Windshield heater	--	2
Flight director computer	1	-
Navigation light	--	1
ac generator tripoff	(6 instances of tripoff)	-
Autopilot	1	-

Table 7.4-1 is a compilation of the indirect effects of 214 lightning-strike incident reports from commercial sources. While outages occur in only a small percentage of all incidents, the systems affected indicate potential problems that are slowly developing due to the following:

- o Increased use of non-metallic aircraft skin.
- o Increased use of solid-state electronics.
- o An increasing dependence on electronics to perform flight-critical functions.

Typical examples are not difficult to find. Probably the best example of dependent solid-state electronics is the digital-fly-by-wire control system that is rapidly being adopted in military aircraft.

7.4.1.2 Design Goals For The Instrumentation Engineer

1. Install the instrumentation wiring and hardware in such a manner as to prevent the indirect effects from damaging either the instrumentation system or the aircraft system. It is very important that the aircraft system is not compromised during the installation of the instrumentation system.
2. Review the instrumentation system installation to be certain that the safety of the aircraft and crew has not been reduced due to the instrumentation system installation.
3. When possible, select or design electronic equipments that can tolerate input/output transients on power and information circuits.
4. Review the trade-offs that must be made between the cost of providing item #3 and the cost of shielding equipments and wiring.
5. The instrumentation engineer must take advantage of the inherent aircraft shielding. Avoid areas where equipment and wiring are exposed to the lightning-generated EMF.
6. If the aircraft is to be subjected to lightning strokes (and precipitation static), physically inspect the aircraft for an up-dated systems approach to lightning and precipitation static control. Spend some time with an operations engineer and be certain that the aircraft workbook reflects all E.O.'s (Engineering Orders) pertaining to lightning and precipitation static protection.

7.4.1.2.1 Location of Equipment

It is readily recognized that the instrumentation engineer may not have much of a choice of where he can install his system. Yet, the use of existing areas can often be optimized. For example, the indirect effects can be minimized by locating electronic equipments in areas where the EMF produced by lightning currents are lowest. Since the most important type of outside-to-inside coupling is through apertures it follows that equipments should be as far away from these apertures as possible. The ideal location is a shielded compartment toward the center of the aircraft away from extremities and outer skin.

7.4.1.2.2 Lightning Protected Access Doors

The need to provide a liquid seal around access doors has led to the use of various gaskets and seals between the door and its mating surface. Most of these seals have little or no electrical conductivity, leaving the metallic fasteners and screws as the only conducting path into the cover. Therefore, suggestions will be offered that, when properly used, will successfully prevent sparking when hit by lightning. The modifications to be made to the access doors are quite easy to do:

1. Remove phenolic and anodized coatings from the clamp ring.
2. Remove anodized coating from mating surfaces of the access door.
3. Sealing the access door to the surrounding skin frame with conductive grease consisting of 35% by weight of aluminum powder and 65% by weight of Aeroshell (or equivalent) 14 grease.

A typical door modified as suggested above had 23 bolts, whereas other doors having over 40 bolts have resisted sparking even with zinc chromate on the mating surfaces.

The importance of adequate electrical conductivity between access doors and their surroundings cannot be overemphasized, particularly if the access doors constitute a large part of the aircraft skin.

7.4.1.2.3 Location of Wiring

When an aircraft is struck by lightning it is forced to assume the electric field potential of the lightning flash at that point. The electric field strength will be greatest about points of small radius of curvature, nose radomes for example. Ref. (B14).

Wiring should be located away from apertures and away from regions where the radius of curvatures are small. The best locations for wiring is close to a ground plane or structural member.

Some basic principles to follow are (see Figure 7.4-1):

1. Maintain all wiring close to a metallic ground plane. This procedure minimizes the amount of flux that can pass between the ground plane and the wiring. (Figure 7.4-1(a)).

2. Magnetic fields are concentrated around protruding structural members and diverge in inside corners. Therefore, place wiring in the base corners instead of on top (Figure 7.4-1(b)).

3. Magnetic fields will be weaker on the interior of a U-shaped channel than on its edges (see Figure 7.4-1(c)).

4. Magnetic fields will be lowest inside a metal conduit (see Figure 7.4-1(d)).

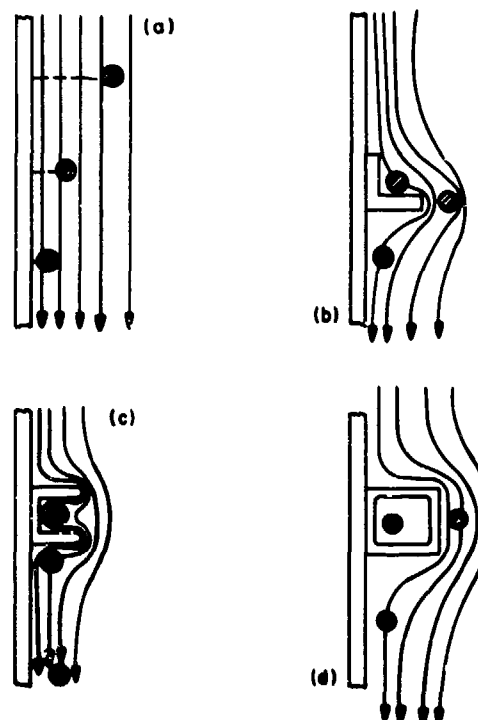


Figure 7.4-1 Flux Linkages vs Conductor Position. Ref. (B14).

7.4.1.2.4 Use of Shielding

Shielding wires and cables against magnetic fields that have been created by lightning requires the shield to be grounded at both ends so that the shield can carry a circulating current. It is this circulating current that cancels the magnetic fields that produce common-mode voltages. The term common-mode voltage in this application refers to the magnetically-induced voltages appearing between a single conductor and the airframe or conductive skin.

The requirement that a shield intended for protection against lightning effects be grounded at both ends raises the discussion of single versus multipoint grounding of circuits. In general, low-level circuits need to be shielded against low frequency interference and shields intended for this purpose are grounded at only one end. Often overlooked is that the physical length of such shields must be short as compared to the wavelength of interfering signals. Lightning-produced interference, however, is usually broad band and include frequencies much higher than those typically considered for low-frequency shield. As a result the needs for both cannot easily be met by the use of one shield system.

Both requirements are usually met by having one shield system to protect against low-frequency interference and a second overall shield system to protect against lightning-generated interference. Within the overall shield the necessary aircraft circuits are independently routed with their own shields and grounding philosophy.

It logically follows that grounding both ends can be improved upon by grounding the shield at multiple mid-points. Most likely the cable will be exposed to a significant amount of magnetic field only at small sections of its total length; thus, the multiple grounding will tend to isolate the circulating currents in only those cable sections affected. Multiple grounds should be carefully planned because it is theoretically possible to sustain standing waves. Therefore, staggered non-uniform spacing of multiple ground points is suggested.

Figure 7.4-2 shows four methods of grounding the overall shield. The best performance is obtained with the 360° connector. The shield makes a 360° circumferential connection to the back shell of the connector (see Figure 7.4-2(b)).

At connectors or junction boxes it is often necessary to group shield grounds together at one point. This practice is difficult and complicated when the same shields are used to prevent lightning strike effects and to protect sensitive circuits as well as trying to prevent cabling radiation interference. In order to reduce these problems remember to group the wiring according to category I-IV guidelines. The groundings must be carefully controlled if overall shields are to be used in addition.

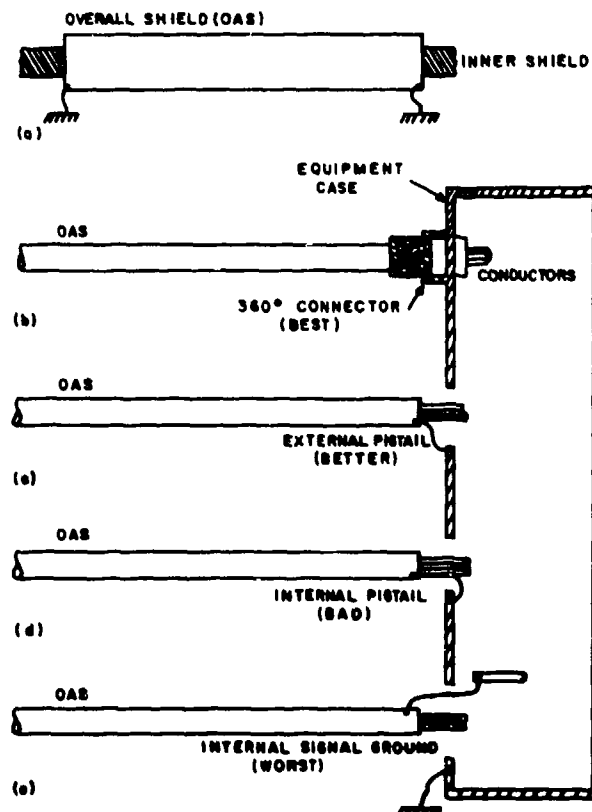


Figure 7.4-2 Types of Grounding for Shields; (Protection From Lightning Hazards). Ref. (B14).

The solid shield provides better shielding than a braided shield, and a spiral-wrapped shield can be far inferior to a braided shield. For severe environments braided shields using two overlapping courses of braid may provide shielding performance equivalent to a solid shield.

Conduits may or may not provide electromagnetic shielding. Oftentimes conduits in aircraft are used more for mechanical protection of conductors. Conduits must be electrically grounded to the airframe structure to be of any use for shielding. For example, conduits used for mechanical protection are often mounted in clamps that use rubber gaskets to prevent mechanical vibration and wear. Such clamps electrically isolate the conduit from aircraft ground.

7.4.1.2.5 Length of Shield Ground Termination Leads

Shields are normally difficult to ground because the length of the termination ground lead tends to be excessive. The reactance of a short, straight termination ground lead is so low at low frequencies (audio range) that it is of no concern. This is particularly true if the diameter of the wire is relatively large so that the ratio of length to diameter is small. But, the effect of this inductance becomes important at higher frequencies. For signals in the audio range, shield-ground lead wires should not exceed 2.5 to 5.0 centimeters (1 to 2 inches).

The practice of grounding an overall shield to the inside surface of an equipment case through a set of connector contacts and a lead wire is less effective than the use of an external lead wire because of the longer length and because the internal method brings the currents directly into the inside of the junction box. Such grounding of an overall shield should be avoided and in no case should an overall shield be connected to a signal ground bus.

7.4.1.2.6 Improvement Through Circuit Design

The studies of the various types of interference produced in an aircraft by the flow of lightning current have shown that oscillatory frequencies are often excited on aircraft wiring, particularly if a single point ground system is used. The frequencies tend to be in the several hundred kilohertz range to a few megahertz. When possible, the pass bands of electronic equipments should not include these frequencies.

Basic considerations concerning circuit design and sensor transmission constitute the majority of the instrumentation engineer's problems. Above all, signal circuits should avoid the use of the aircraft structure as a return path. If the structure is used as a return, the resistively-generated voltage drops will be included in the signal path. However, sensor signal transmission over a twisted-pair circuit with signal grounds isolated from aircraft structure will tend to couple lower voltages in the signal path.

7.4.2 Precipitation Static

An aircraft flying through dry precipitation in the form of sleet, hail, ice crystals or even dust or sand will absorb a charge from these particles as they impact the aircraft. Viewed as electrostatics, the aircraft in flight is a capacitor with the surrounding space as the other electrode. The impacting particles deposit a net charge on the aircraft due to the frictional charging (triboelectric effect).

7.4.2.1 Discharge Characteristics

The capacitance of a large aircraft (Boeing 707) in flight is around 1000 picofarads and the potential difference between the aircraft and surrounding space rapidly approaches several hundred thousand volts. These large potentials create very intense electric fields around the aircraft particularly at the trailing edges of the airfoil surfaces and at the tip of any metallic projection such as an antenna. When these field gradients reach a critical level, about 7.5 Kvolt/centimeter (19.1 Kvolt/inch) at 11 kilometers (36,000 feet), the surrounding air is ionized and a corona discharge occurs. The discharge is in the form of a train of pulses with very short rise times (0.01 microsecond) followed by an exponential decay. A similar phenomenon can occur in clear air, when the aircraft develops a net charge due to ion transport in the engine exhaust. However, engine charging currents are small as compared to heavy triboelectric charging.

Three types of ionization of the surrounding air can occur when an aircraft is charged by precipitation: Refs. (72, 73).

1. Corona Breakdown - Corona discharges occur at the sharp extremities of the airframe where the radius of curvature is very small. The amplitude of the individual corona pulses are proportional to the altitude and to the radius of curvature of the discharge point. The corona discharge pulses occur as a regularly spaced pulse train. The pulse repetition frequency of the corona pulse train is pro-

portional to the dc discharge current. Note that the family of curves (Figure 7.4-3) are altitude dependent, relatively flat below about 1 MHz and then decrease at 6 dB/octave above 3 MHz.

2. Streamering - This phenomenon occurs between bound charges developed on dielectric surfaces, such as radomes and windows, and the surrounding metallic portions of the aircraft.

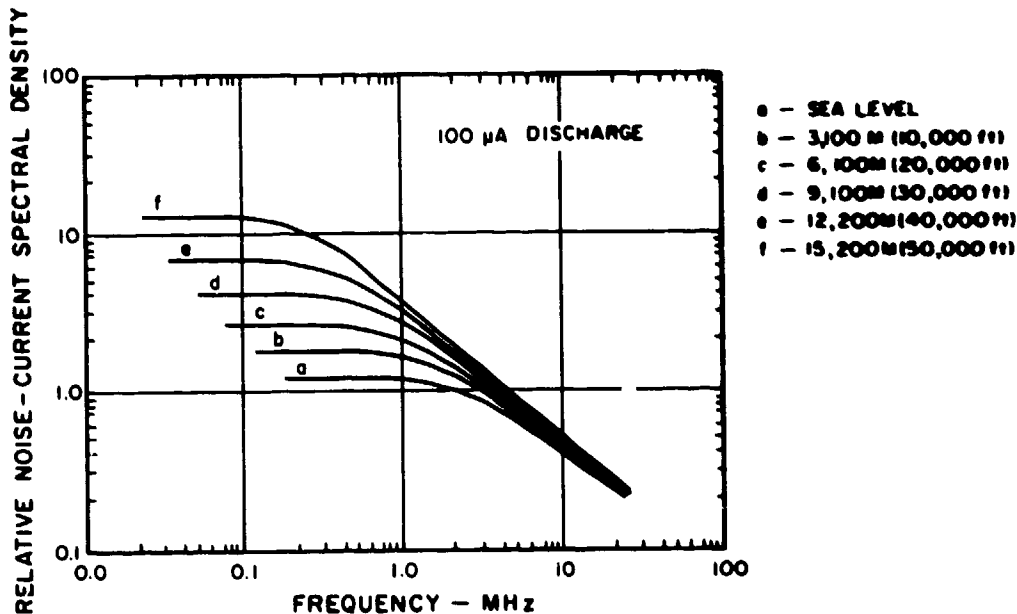


Figure 7.4-3 Normalized Noise Spectrum from Trailing Edge. Ref. (72).

Streamering is triboelectric in origin and is not caused by engine charging. Streamering amplitudes are large and their occurrence is irregular, and, unlike corona discharges, the noise spectrum is also irregular. Streamering is controlled by conducting surface coatings rather than by use of P-static dischargers.

3. Sparking - This third and final phenomenon occurs between two metallic surfaces that are dc isolated and are triboelectrically charged to different potentials because of their size differences. Examples are external antennas and lightning diverter strips. The spark occurs when the dielectric strength of the insulation is exceeded. The sparks consist of very sharp pulses with a "white-noise" spectrum. Most of the P-static observed at VHF communications frequencies is due to sparking. Sparking is controlled by dc bonding and not by dischargers.

All three types of noise can be present under natural triboelectric charging conditions.

7.4.2.2 The Role of the Instrumentation Engineer

So far the basics of precipitation static appear to be only academic with little or no relevance to the instrumentation engineer; indeed, this may be so. However, in some circumstances, the instrumentation engineer may have responsibility for evaluating navigation systems and their antennas. For these circumstances the effects of P-static is very important.

The noise that is present in the absence of corona discharge depends on the receiving system considered. Ignoring man-made noise, it is always atmospheric noise for LF and MF radios (eg., ADF, Loran C/D and Decca), always internal circuit noise for VHF (eg., VOR and VHF comm), and atmospheric or internal circuit noise for HF receivers.

7.4.2.2.1 Effects of P-Static on Navigation Subsystems

Precipitation static can cause a deviation indicator, VHF Omirange (VOR), Localizer (LOC), and Glide Slope (GS) equipment to present false indication without showing a warning flag. P-static induces course errors in VOR receivers and causes misalignment in LOC and GS receivers. These effects have been demonstrated on all navigation equipment tested to date. The problem is apparently caused by shock excitation of the receiver tuned circuits.

7.4.2.2.2 Antenna Factors

Exposed metal antenna components should be insulated with polyethylene or some other suitable material so that they do not come in contact with charged airborne particles. An insulated antenna also prevents a corona discharge directly from the antenna.

Since static charges concentrate at areas of small radii antennas should be installed as far away from these areas as possible. For example: A fin cap located Loran C/D antenna is particularly vulnerable to corona noise. However, a belly mounted installation that uses the ADF sense antenna (with a suitable multi-coupler) is far less vulnerable to P-static.

7.4.2.2.3 Static Discharges

The static discharge phenomenon can be controlled by use of a specially designed electrostatic discharger, Figure 7.4-4. Refs. (74, 75).

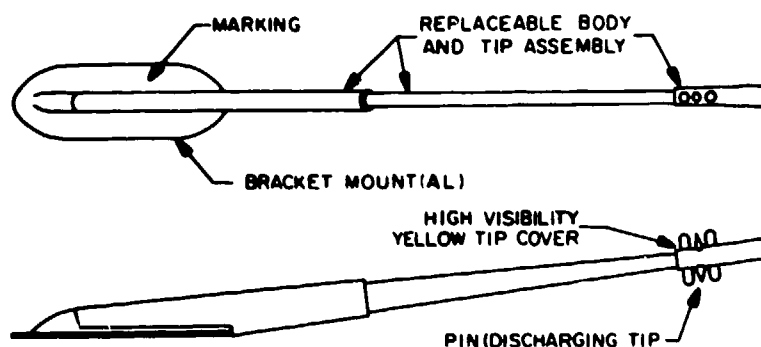


Figure 7.4-4 Typical Null Field Type Electrostatic Discharger

Present day electrostatic dischargers permit a satisfactory solution to the P-static problem. They have no effect on the lightning problem and will neither attract nor divert lightning strikes.

There are basically two types of static dischargers: active and passive.

1. The active discharger utilizes circuitry to reduce the static charge on an aerospace vehicle. One type uses the thermionic emission principle to "boil" off excess electrons. Being independent of airflow, this type is adaptable to space vehicles.
2. Figure 7.4-4 represents the passive type of discharger most commonly used on jet aircraft. In the past, static discharge wicks were used to reduce the charge on the aircraft. However, because of the high speeds of modern jet aircraft and the fact that they are powered by jet engines which tend to increase static charges, it became necessary to develop static-discharge devices that were more effective than the wicks formerly used. This new type (Figure 7.4-4) is called a Null Field Discharger and was developed by Granger Associates, Ref. (75). They produce a discharge field which has minimum coupling with radio antennas. Ref. (B15).

7.4.2.2.4 The Design of a P-Static Protection System

Fortunately, several aircraft of varying size have been successfully protected by discharger installations and it is these aircraft that can be used as a basis for similar system designs. Thus, in actual practice the aircraft engineer is more concerned with specific discharger design, the number of dischargers and their location. Most of these decisions can be approached by using well-developed scaling rules.

Dischargers should be located at or near the maximum field concentration points to insure that corona discharges will always occur through the discharger and not from some other airframe location. Because of mutual shielding, wing located dischargers need not be closer than about 30 centimeters (12 inches) and except for the wingtip dischargers 60 centimeters (24 inches) is typical.

The tip dischargers serve a particular purpose. At this point localized low pressures associated with the tip vortex result in unusually high discharge currents when the breakdown field concentration is exceeded. The tip dischargers control the noise from this discharge and position the ion cloud which trails aft from it so as to provide a "space-charge shield" around the critical airfoil tip extremity. Probe-type HF antennas are vulnerable to corona and special high density dischargers must be installed at these extremities.

It may be of assistance to recognize conventional discharger installations. Typical large aircraft shapes will use dischargers at the trailing wing tips, the trailing tip of the vertical fin and the trailing tips of the horizontal stabilizer whether it is conventional or a "T" tail.

7.4.2.2.5 Aircraft Inspection

The average flight test operations engineer usually knows very little about the types of P-static unless he is accustomed to flying in that type environment. As a result, noise that appears in the communications and navigation systems is usually brought to the attention of the instrumentation engineer. General knowledge concerning P-static can be very useful at a time like this and can often times point to an aircraft with deficient P-static dischargers or none at all.

8.0 REFERENCES

Books

- B1 Bazovsky, Igor, "Reliability Theory and Practice," Second Printing, Published in USA by Prentice Hall, 1962. Chapters Five, Six, and Seven.
- B2 Wright Patterson Air Force Base, Airforce Systems Command Design Handbook Program, General Series; "Environmental Engineering", DH 1-5, Revision 5, USA, Sept 1973.
- B3 Wright Patterson Air Force Base, Airforce Systems Command Design Handbook Program, General Series; "Electromagnetic Compatibility", DH 1-4, Revision 3, USA, July, 1973.
- B4 Wright Patterson Air Force Base, Airforce Systems Command Design Handbook Program, General Series; "System Safety", DH 1-6, Revision 4, USA, July, 1973.
- B5 White, Donald R. J., "A Handbook Series On Electromagnetic/Interference and Compatibility," First Edition, Published in USA by Don White Consultants, Inc., Germantown, Maryland. 1973, Volume III.
- B6 Ruzicka, Jerome E.; Derby, Thomas F.; "Influence of Damping in Vibration Isolation," Published in USA by the Shock and Vibration Information Center, U.S. Department of Defense, Library of Congress Catalog Card Number 71-611802, Contract Number N00173-68-C-0072, 1971, Chapter One.
- B7 Everitt, William L.; editor, "Physical Design of Electronic Systems," First Edition, Published in USA by Prentice-Hall, 1970, Volume I.
- B8 Westman, H.P., Editor "Reference Data for Radio Engineers," Fourth Printing, Published in USA by American Book-Stratford Press, Inc., New York, 1975, Page 52.
- B9 Stein, Peter K.; "Measurement Engineering," Arizona State University, Tempe, Arizona. Third Edition, printed by Imperial Litho, Phoenix, Arizona, 1964, Volume I.
- B10 Stiltz, Harry L.; "Aerospace Telemetry," Second Printing, Published in USA by Prentice Hall, 1963, Chapter Eleven.
- B11 Pollard, Frank B., Arnold, Jr., Jack H.; Editors, "Aerospace Ordnance Handbook, Published in USA by Prentice Hall, 1966, Chapter Eight.
- B12 Reed, Henry R., Russell, Carl M.; "Ultra High Frequency Propagation," Published in USA and Britain by John Wiley and Sons, Inc., New York and Chapman and Hall, Limited, London, 1953, page 330.
- B13 Schelkunoff, Sergei A., Friis, Harald T.; "Antennas - Theory and Practice," Published in USA and Britain by John Wiley and Sons, Inc., New York and Chapman and Hall, Limited, London, 1952, Page 299.
- B14 Fisher, Franklin A., Plumer, J. Anderson; "Lightning Protection of Aircraft," Published in USA. NASA Reference Publication 1008, October 1977, pp. 429 through 437.
- B15 McKinley, James L., Bent, Ralph D., "Electricity and Electronics for Aerospace Vehicles," Second Edition, New York, N.Y., McGraw Hill Book Company, Published in USA, 1971, page 7.

Reports and Publications

- 1. "Standard General Requirements for Electronic Equipment." MIL-STD-454.
- 2. "Flight Testing, Electrical Systems, Piloted Aircraft and Guided Missile, General Requirements For." MIL-F-25381.
- 3. "Climatic Extremes for Military Equipment." MIL-STD-210.
- 4. MIL-W-5088, "Wiring, Aerospace Vehicle."
- 5. "Electrical Systems, Aircraft, Design and Installation of, General Specifications." MIL-E-25499.
- 6. "Thermal Performance Evaluation, Airborne Electronic Equipment, Equipment, General Requirements For." MIL-T-23103.
- 7. "Electromagnetic Compatibility Requirements, Systems." MIL-E-6051.

8. "Electromagnetic Interference Characteristics Requirements for Equipment." MIL-STD-461.
9. HRB-Singer, Inc., "Maintainability Handbook for Electronic Equipment Design," Technical Report NAVTRADEVCEM 330-1-4. April 4, 1960, DDC No AD 241284.
10. Headquarters, Department of the Army, Maintainability Engineering, June 1966. Pamphlet 705-1.
11. "Electrical Equipment; Aircraft, Selection and Installation Of." MIL-E-7080.
12. "Drawings, Engineering and Associated Lists." MIL-D-1000.
13. "Drawings, Installation, and Preliminary Data (for Electronic and Related Equipment)." MIL-D-16415.
14. Electronic Industries Assoc., "Designer's Guide on Electromagnetic Compatibility - Cabling of Electronic Equipment." March 1965, Electromagnetic Compatibility Bulletin No. 8, 26 pp.
15. Carlson, B. L., Marcelja, W. R., and King, D. A.; Aero-Space Div., The Boeing Co., "Computer Analysis of Cable Coupling for Intra-System Electromagnetic Compatibility." May 1965, AFAL-TR-65-142, DDC No. AD 465040.
16. "Electromagnetic Compatibility." MSFC-SPEC-279.
17. Wilson, T. R., and Skene, W. M.; The Boeing Co., "Bonding and Grounding in Aerospace Vehicles and Ground Equipment," Aerospace Group File No. B-8.
18. "Bonding Electrical, and Lightning Protection, for Aerospace Systems." MIL-B-5087.
19. U. S. Department of Commerce, Office of Technical Services, "Bonding Materials, Metallic Mating Surfaces: Low RF Impedance," January 1954. Report PB 111930.
20. Craft, Arnold M., IEEE Transactions on Electromagnetic Compatibility, "Considerations in the Design of Bond Straps," October 1964. Vol. EMC-6, No. 3., pp. 58-65.
21. Lord Kinenatics, Lord Corporation, Erie, Pennsylvania, USA, Catalog LB-370.
22. "Connectors, Electrical, Circular Miniature, High Density, Quick Disconnect (Bayonet, Threaded, and Breech Coupling), Environment Resistant, Removable Crimp and Hermetic Solder Contacts, General Specifications For," 7 December 1977. MIL-C-38999 G.
23. Amphenol North America Division, Bunker-Ramo Corp., Oak Brook, Illinois, Series 48 Connector Specifications. MIL-C-26500/38300/26518, [Ca. 1962], pp 2-12.
24. USAF, "Connectors, Electrical, Circular, Multicontact, High Environment, Quantitative Reliability, General Requirements For." MIL-C-38300.
25. "Gold Plating, Electro Deposited." MIL-G-45204.
26. Lawrence, Roland; Deutsch Electronic Components Division, "Electrical/Electronic Inter-connection Systems." Third Edition, Banning, Calif., The Deutsch Co., 1975.
27. USAF, "Connectors, General Purpose, Electrical Miniature, Circular, Environment Resisting, General Specifications For." MIL-C-26500.
28. "Marking for Aircrew Station Displays, Design Configuration Of." MIL-M-18012.
29. Switches and Switch Assemblies, Sensitive and Push, Snap Action, General Specification For." MIL-S-8805.
30. "Human Engineering Requirements for Military Systems, Equipment and Facilities." MIL-H-46855.
31. "Fuses, Fuseholders, and Associated Hardware, Selection and Use Of." MIL-STD-1360.
32. Bussman Mfg Division, McGraw-Edison Company, St. Louis, Missouri; Form FIS, dated March, 1975.
33. Bussman Mfg Division, McGraw-Edison Company, St. Louis, Missouri; Form SFB, no date.
34. "Circuit Breakers, Selection and Use Of." MIL-STD-1498.

35. "Circuit Breaker, Trip-Free, Aircraft, General Specification For." MIL-C-5809.
36. System Designer's Handbook, "Circuit Breaker Selection Procedures," July 1966.
37. Texas Instruments, Incorporated, Circuit Breaker Department; Attleboro, Massachusetts; Bulletin Number CIRB-10F, CIRB-23E.
38. "Fuse, Current-Limiter Type, Aircraft." MIL-F-5372.
39. "Wire, Electrical, 600 Volt, Copper Aircraft." MIL-W-5086.
40. "Cable, Electric, Aerospace Vehicle, General Specification For." MIL-C-7078.
41. "Wire, Electrical, 600 Volt, Aluminum Aircraft." QPL-7072 (MIL-W-7072).
42. "Wire, Electric, Polyimide-Insulated, Copper or Copper Alloy." MIL-W-81381.
43. "Identification Coding and Application of Hook Up Wire." MIL-STD-681.
44. "Guidance for Flexible Flat Multiconductor Cable (Flat Conductors) 1972. MIL-HDBK-176 (DOD).
45. Belden Corporation, Electronic Division, Dept. EM, Richmond, Virginia; Flat Cable, Bonded, Style 2697, 2651 and 2884.
46. "Flat Conductor Cable Connector Survey," Technical Utilization Officer, Marshall Space Flight Center, Code A&PS-TU, Marshall Space Flight Center, Alabama 35812, USA. Reference: B73-10055.
47. "Flat Conductor Cable Connector Survey," published USA, NASA, Washington, D.C., 1970. NASA TM X-64613.
48. Angele, Wilhelm, "Flat Conductor Cable for Electrical Packaging," published USA, NASA, Washington, D. C., 1972. NASA TM X-64667.
49. "Crimping of Electrical Connections, Requirements For." MSC/MSFC-JD-001.
50. "Terminal Junction Systems, General Specification For." MIL-T-81714.
51. NASA, "Manufacture and Quality Control of Interconnecting Wire Harness," 1972. NASA TM X-64685, Vol. IV of IV.
52. Raychem Corporation, "Solder Sleeve and Termashield Installation Procedures," 1974 D-239-2.
53. "Electronic Engineers Master Catalog," (EEM), Published in the USA by United Technical Publishers, Garden City, New York, 22nd Edition, 1979-80. Volume I.
54. Caso, Louis F., "Approximating Cable Diameter," Design News, Vol. 25, No. 1, January 5, 1970.
55. NASA "Flight Assurance Testing (Environmental) Electronic and Electromechanical Equipment," 1969 DFRC Process Specification 21-2.
56. "Electronic Equipment, Airborne, General Specification For", MIL-E-5400.
57. Weinstock, G. L.; "Electromagnetic Interference Control Within Aerospace Ground Equipment for the McDonnell Phantom II Aircraft," McDonnell Aircraft Corporation, St. Louis, Missouri, 1965.
58. Filtron Company, Inc., for the U. S. Army Electronics Lab , Ft. Monmouth, New Jersey. "Interference Reduction Guide for Design Engineers," Published in the USA, 1964, Volume I, DDC No. AD 619666, Vol II, DDC No AD 619667.
59. King, G. J., "Achieving Electromagnetic Compatibility by Control of the Wiring Installation, Ninth Tri-Service Conference on Electromagnetic Compatibility, IEEE October 1963, page 193-204.
60. McKerchar, W. D.; "Electromagnetic Compatibility Program for the McDonnell RF-4C Phantom II Aircraft, Ninth Tri-Service Conference on Electromagnetic Compatibility, IEEE October 1963, page 719.
61. Metex Corporation, "EMI Shielding Materials, Gaskets and Components; Catalog and Handbook," 1970, Issue ME-34.
62. Webb, Lannie D.; "Characteristics and Use of X-15 Air-Data Sensors," NASA TN D-4597, June 1968. Pages 17 and 18.
63. Kottkamp, Kohl, Wilhelm FRG/VFW-Fokker, "Strain-gauge Measurements on Aircraft". AGARDograph 160, Vol 7.

64. The Boeing Company, Houston, Texas, "Sneak Circuit, Sample Reports," 1973.
65. The Boeing Company, Houston, Texas, "Sneak Circuit Analysis of F8 Digital Fly-by-Wire Aircraft," D2-118582-1, 1976.
66. The Boeing Company, Houston, Texas, "Sneak Circuit Analysis of the Shuttle Training Aircraft," NASA Johnson Space Center Report No. JSC 10626, January 1976.
67. USAF, "Electroexplosive Subsystems, Electrically Initiated, Design Requirements and Test Methods" MIL-STD-1512.
68. "Installation and Test of Aircraft Pyrotechnic Equipment in Aircraft, General Specification For" MIL-I-8672.
69. Mohrbach, Paul F., Wood, Robert F.; The Franklin Institute Research Laboratories. "Effects of Radio Frequency Stimuli on Electroexplosive Devices," June 1967. Proceedings of the 5th Symposium on Electroexplosive Devices.
70. IEEE Standard Test Procedures for Antennas (revised 1979) Std 149 - 1979.
71. Hacker, Paul T.; NASA, "Lightning Damage to a General Aviation Aircraft-Description and Analysis," TN D-4597, 1974.
72. Tanner, R. L., Manevitz, J. E.; Proceedings of the IEEE, "An Analysis of Corona-Generated Interference in Aircraft," January 1964, page 44.
73. Manevitz, J. E., Tanner, R. L.; Proceedings of the IEEE, "Some Techniques for the Elimination of Corona Discharge Noise in Aircraft Antennas," January 1964, pages 55, 56, and 57.
74. "Dischargers, Aircraft Electrostatic, General Specifications For" MIL-D-9129.
75. Granger, John V. N., Granger Associates, "Precipitation Static Protection for Jet Aircraft, a Summary," 1968, Department of Transportation Library Number TAD-494.6, pp 17-21.

REPORT DOCUMENTATION PAGE											
1. Recipient's Reference	2. Originator's Reference AGARD-AG-160 Volume 13	3. Further Reference ISBN 92-835-1399-1	4. Security Classification of Document UNCLASSIFIED								
5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 Rue Ancelle, 92200 Neuilly sur Seine, France										
6. Title	PRACTICAL ASPECTS OF INSTRUMENTATION SYSTEM INSTALLATION										
7. Presented at											
8. Author(s)/Editor(s) R.W. Borek			9. Date September 1981								
10. Author's/Editor's Address Flight Mission Operations NASA Dryden Flight Research Center Post Office Box 273 Edwards, CA. 93523, USA			11. Pages 198								
12. Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.										
13. Keywords/Descriptors											
<table border="0"> <tbody> <tr> <td>Flight tests</td> <td>Electric wire</td> </tr> <tr> <td>Test equipment</td> <td>Wiring</td> </tr> <tr> <td>Measuring instruments</td> <td>Aircraft</td> </tr> <tr> <td>Installing</td> <td></td> </tr> </tbody> </table>				Flight tests	Electric wire	Test equipment	Wiring	Measuring instruments	Aircraft	Installing	
Flight tests	Electric wire										
Test equipment	Wiring										
Measuring instruments	Aircraft										
Installing											
14. Abstract											
<p>This AGARDograph is the 13th of the AGARD Flight Test Instrumentation Series and outlines some of the factors that influence the development of an instrumentation system installation. The volume was not written with the intention of being a design handbook and therefore the guidelines presented are in most cases given as suggestions.</p> <p>The material is presented in a progressive manner starting with a review of the mission profile requirements. Included are such factors as environment, reliability and maintainability, and system safety.</p> <p>The assessment of the mission profile is followed by an overview of electrical and mechanical installation factors. The material presented is primarily directed at shock/vibration isolation systems and standardization of the electrical wiring installation, two factors often overlooked by instrumentation engineers.</p> <p>A discussion of installation hardware reviews the performance capabilities of wiring, connectors, fuses and circuit breakers, and so forth. Information is provided to guide proper selections.</p> <p>The discussion of the installation is primarily concerned with the electrical wire routing, shield terminations and grounding. Also included are some examples of installation mistakes that could affect system accuracy.</p> <p>The remaining two sections discuss system verification procedures and special considerations such as sneak circuits, pyrotechnics, aircraft antenna patterns, and lightning strikes.</p> <p>This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.</p>											

<p>AGARDograph No. 160 - Volume 13 Advisory Group for Aerospace Research and Development, NATO PRACTICAL ASPECTS OF INSTRUMENTATION SYSTEM INSTALLATION R.W. Borek Published September 1981 198 Pages</p> <p>This AGARDograph is the 13th of the AGARD Flight Test Instrumentation Series and outlines some of the factors that influence the development of an instrumentation system installation. The volume was not written with the intention of being a design handbook and therefore the guidelines presented are in most cases given as suggestions.</p> <p>The material is presented in a progressive manner starting with a review of the mission profile requirements.</p> <p>P.T.O.</p>	<p>AGARD-AG-160 Vol. 13</p> <p>Flight tests Test equipment Measuring instruments Installing Electric wire Wiring Aircraft</p>	<p>AGARDograph No. 160 - Volume 13 Advisory Group for Aerospace Research and Development, NATO PRACTICAL ASPECTS OF INSTRUMENTATION SYSTEM INSTALLATION R.W. Borek Published September 1981 198 Pages</p> <p>This AGARDograph is the 13th of the AGARD Flight Test Instrumentation Series and outlines some of the factors that influence the development of an instrumentation system installation. The volume was not written with the intention of being a design handbook and therefore the guidelines presented are in most cases given as suggestions.</p> <p>The material is presented in a progressive manner starting with a review of the mission profile requirements.</p> <p>P.T.O.</p>	<p>AGARD-AG-160 Vol. 13</p> <p>Flight tests Test equipment Measuring instruments Installing Electric wire Wiring Aircraft</p>
<p>AGARDograph No. 160 - Volume 13 Advisory Group for Aerospace Research and Development, NATO PRACTICAL ASPECTS OF INSTRUMENTATION SYSTEM INSTALLATION R.W. Borek Published September 1981 198 Pages</p> <p>This AGARDograph is the 13th of the AGARD Flight Test Instrumentation Series and outlines some of the factors that influence the development of an instrumentation system installation. The volume was not written with the intention of being a design handbook and therefore the guidelines presented are in most cases given as suggestions.</p> <p>The material is presented in a progressive manner starting with a review of the mission profile requirements.</p> <p>P.T.O.</p>	<p>AGARD-AG-160 Vol. 13</p> <p>Flight tests Test equipment Measuring instruments Installing Electric wire Wiring Aircraft</p>	<p>Included AGARDograph No. 160 - Volume 13 Advisory Group for Aerospace Research and Development, NATO PRACTICAL ASPECTS OF INSTRUMENTATION SYSTEM INSTALLATION R.W. Borek Published September 1981 198 Pages</p> <p>This AGARDograph is the 13th of the AGARD Flight Test Instrumentation Series and outlines some of the factors that influence the development of an instrumentation system installation. The volume was not written with the intention of being a design handbook and therefore the guidelines presented are in most cases given as suggestions.</p> <p>The material is presented in a progressive manner starting with a review of the mission profile requirements.</p> <p>P.T.O.</p>	<p>AGARD-AG-160 Vol. 13</p> <p>Flight tests Test equipment Measuring instruments Installing Electric wire Wiring Aircraft</p>

<p>Included are such factors as environment, reliability and maintainability, and system safety.</p> <p>The assessment of the mission profile is followed by an overview of electrical and mechanical installation factors. The material presented is primarily directed at shock/vibration isolation systems and standardization of the electrical wiring installation, two factors often overlooked by instrumentation engineers.</p> <p>A discussion of installation hardware reviews the performance capabilities of wiring, connectors, fuses and circuit breakers, and so forth. Information is provided to guide proper selections.</p> <p>The discussion of the installation is primarily concerned with the electrical wire routing, shield terminations and grounding. Also included are some examples of installation mistakes that could affect system accuracy.</p> <p>The remaining two sections discuss system verification procedures and special considerations such as sneak circuits, pyrotechnics, aircraft antenna patterns, and lightning strikes.</p> <p>This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.</p> <p>ISBN 92-835-1399-1</p>	<p>Included are such factors as environment, reliability and maintainability, and system safety.</p> <p>The assessment of the mission profile is followed by an overview of electrical and mechanical installation factors. The material presented is primarily directed at shock/vibration isolation systems and standardization of the electrical wiring installation, two factors often overlooked by instrumentation engineers.</p> <p>A discussion of installation hardware reviews the performance capabilities of wiring, connectors, fuses and circuit breakers, and so forth. Information is provided to guide proper selections.</p> <p>The discussion of the installation is primarily concerned with the electrical wire routing, shield terminations and grounding. Also included are some examples of installation mistakes that could affect system accuracy.</p> <p>The remaining two sections discuss system verification procedures and special considerations such as sneak circuits, pyrotechnics, aircraft antenna patterns, and lightning strikes.</p> <p>This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.</p> <p>ISBN 92-835-1399-1</p>
<p>Included are such factors as environment, reliability and maintainability, and system safety.</p> <p>The assessment of the mission profile is followed by an overview of electrical and mechanical installation factors. The material presented is primarily directed at shock/vibration isolation systems and standardization of the electrical wiring installation, two factors often overlooked by instrumentation engineers.</p> <p>A discussion of installation hardware reviews the performance capabilities of wiring, connectors, fuses and circuit breakers, and so forth. Information is provided to guide proper selections.</p> <p>The discussion of the installation is primarily concerned with the electrical wire routing, shield terminations and grounding. Also included are some examples of installation mistakes that could affect system accuracy.</p> <p>The remaining two sections discuss system verification procedures and special considerations such as sneak circuits, pyrotechnics, aircraft antenna patterns, and lightning strikes.</p> <p>This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.</p> <p>ISBN 92-835-1399-1</p>	<p>Included are such factors as environment, reliability and maintainability, and system safety.</p> <p>The assessment of the mission profile is followed by an overview of electrical and mechanical installation factors. The material presented is primarily directed at shock/vibration isolation systems and standardization of the electrical wiring installation, two factors often overlooked by instrumentation engineers.</p> <p>A discussion of installation hardware reviews the performance capabilities of wiring, connectors, fuses and circuit breakers, and so forth. Information is provided to guide proper selections.</p> <p>The discussion of the installation is primarily concerned with the electrical wire routing, shield terminations and grounding. Also included are some examples of installation mistakes that could affect system accuracy.</p> <p>The remaining two sections discuss system verification procedures and special considerations such as sneak circuits, pyrotechnics, aircraft antenna patterns, and lightning strikes.</p> <p>This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.</p> <p>ISBN 92-835-1399-1</p>